THE BUILDING OF THE BRITISH ISLES

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A HISTORY OF THE CONSTRUCTION AND GEOGRAPHICAL EVOLUTION OF THE BRITISH REGION

BY

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PREFACE

It is now eighteen years since the last edition of this work was issued, and each of these years has augmented our knowledge of the geological structure of the British Islands by some important particulars. In some places outcrops or remnants of certain formations have been discovered where their existence was not previously known; in other areas the succession of the rock-groups and their relations to one another have been more fully examined and worked out. In the case of some formations the succession of their component beds has been determined by the more complete study of their fossils, and by the establishment of zonal subdivisions. Other writers, again, have described the materials composing this or that formation, and have discussed the sources from which these materials appear to have been derived.

The progress of Geological Science has, in fact, been so great that I have found it necessary to rewrite every chapter of the book in order to embody the fresh evidence which has been obtained, and to reconsider all the facts so as to form a better conception of the geographical conditions which prevailed during each successive geological period.

As stated in the Preface to the First Edition, "the aim of this volume is the restoration of the physical and geographical conditions which prevailed in the British area during each of the great periods of time which make up our geological sequence. The pioneer in this branch of Geological Science was Mr. Godwin-Austen, whose masterly essays, published in the *Quarterly Journal of the Geological Society* between 1856 and 1866, may still be read with advantage, for many of his conclusions have been confirmed by the information subsequently derived from deep borings in the eastern and midland counties."

The first systematic treatise on the geographical phases of the British region was that by Professor Hull, published in 1882 and entitled *Contributions to the Physical History of the British Isles*; but the evidence for each geographic restoration was not very fully discussed in that book.

In the first two editions of this work I endeavoured to present the evidence as fully as the available information then allowed. In the present edition, without curtailing the sections devoted to geographic restoration, I have given more detailed accounts of certain episodes in the history of our country which were more especially concerned in the building up of its structural components. In so doing I have had to include brief references to the geological structure of North-Western Europe, for the British area is but a portion of this larger region, and the separation of Great Britain from the continent of Europe is but a minor and very recent incident in the geological history of the region.

I have also dealt more fully with the land-surfaces of Tertiary times, and with the gradual development of the principal physical features of the British Isles, its hills and mountains, plains and valleys. In view of this expansion of the book I have omitted the chapter on the supposed permanence of continents and oceans, for a proper treatment of that subject would occupy much more space, and would really require a volume to itself.

The number of illustrations has been greatly increased, thanks to the free hand allowed me by Mr. Stanford. Many new structural maps have been inserted, and the geographical restoration-maps have all been carefully drawn in accordance with the modified conclusions arrived at in the text. Some photographic views have also been inserted, with the object of illustrating the marked unconformity of certain formations and other physical features of special interest. Two of these views have been obtained from the collection of H.M. Geological Survey, and have not previously been published.

Finally, I may say that I have endeavoured to make myself acquainted with all the known facts about each formation which have a bearing on the subject of the book, and in most cases I have sought information from some one who had studied the particular group of rocks in question. I shall, however, be grateful to any one who will point out facts which I have failed to take into consideration, for no one knows better than myself how difficult it is for one man to deal with all the problems that present themselves for solution in the course of such a history as I have attempted in this book.

My thanks are due to many friends and correspondents for information and advice: especially to Canon Bonney for assistance in preparing the chapter on the Archæan rocks, and in rewriting that on the Trias; to Dr. J. E. Marr for reading my account of the Ordovician period, and for notes on other points; to Dr. Wheelton Hind and Professor T. T. Groom for information about Carboniferous rocks; to Mr. C. T. Clough for assistance in several matters relating to Scotland. I am also indebted to Mr. G. Dollfus for particulars about the Eocene and Oligocene beds of the Paris Basin, and to Mr. Osborne White for reading and commenting on the chapters relating to the Tertiary epochs.

A. J. JUKES-BROWNE.

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CHAPTER I

INTRODUCTION

Geographical Evolution.—The object of this volume is to treat the geological history of the British Islands from a geotectonic and geographic point of view, that is to say, to deal with the physical conditions under which the successive rock-groups were formed; the rocks themselves being described only so far as is necessary for ascertaining whence their component materials were derived, in order to form some conception of the relative position of land and water during each of the successive periods of geological time.

The existing geographical and physical contours of the British Islands are the outcome of the long and varied geological history pertaining to this particular part of the world. There are few other regions of the earth's surface which in so small an area exhibit so many different systems of rocks as are to be found in the British Islands. England alone includes portions of nearly all the rock-systems which are found on the continent of Europe.

Each of these rock-groups was formed during the maintenance of certain physical and geographical conditions which were different from the conditions both of the preceding and of the subsequent periods. When, therefore, we are able to form some definite conception of the geography of the British region during one particular period of past time, we are restoring one phase in the geographical evolution of our islands.

In the multiplicity of rock-groups we have proof that changes in the physical conditions of the region have been frequent, and it becomes evident that the history of its evolution is a long one; it is, in fact, a history of alternate upheaval and depression, of the repeated formation of islands and continents, and of their subsequent detrition and submergence. In this long succession of changes there have been many different arrangements of land and sea over the area where the British Isles now stand; every part of our country has been repeatedly depressed beneath the sea, though some parts have been submerged much more frequently than others, and conversely every part of the area which is now covered by the environing seas has more than once been part of the dry land. Sometimes nearly the whole area has formed part of continental land, and at other times it has been almost entirely submerged beneath the ocean.

Of the earlier phases in this long series of changes we can never learn so much as we know about those which were less remote from the time of human history. Of the islands which were formed, raised, and combined into continental land, and of the continents which were broken up into islands, or replaced by seas during early Palæozoic times, we can only obtain dim and partial glimpses. To the student of Palæozoic geology these glimpses form a kaleidoscopic succession of geographical combinations which, on account of our deficient knowledge, seem to have little relation to each other. Further discoveries will doubtless enlarge our knowledge, and may enable us to construct a more complete series of pictures or maps of these early times, but the records are too fragmentary to supply material for anything like a complete history.

We can, however, look back to a midway epoch in the geographical history of Britain when the foundations of our islands had been laid, and when the older and more mountainous parts of the country had been brought into the relative positions which they now occupy. We may, in fact, regard the Palæozoic districts of the British Islands as portions of an ancient land which has been broken up and reduced to its present dimensions during successive periods of erosion and denudation ; these tracts and the vanished lands of which they formed part have yielded the materials that compose the more recent (Neozoic) strata, and there were at least three periods in these later times when Neozoic strata filled up the gaps between the older blocks of ground and welded the British Islands into a continental whole. Erosion and submergence, however, again began the work of destruction and separation, with the ultimate result of reducing them once more to the state of islands and of giving them the outlines which they now present.

The Geological Evidence.—Before proceeding to describe the successive phases of this process of geographical evolution, some consideration of the evidence on which we have to rely in trying to restore the geography of any period seems to be desirable. The greater part of the strata with which the geologist has to deal are marine deposits, and it is not often that actual proof of the former existence of land in any district is furnished by the intercalation of purely fresh-water deposits. Occasionally we meet with estuarine beds which indicate the close proximity of land; and of more frequent occurrence are conglomerates and pebble-beds recalling those which are formed along modern beaches. But in many cases the position of the land tracts during a given period can only be inferred from general considerations, such as the changes in the lithological characters of the sediments, the thinning or thickening of beds in certain directions, their entire absence in certain areas, their conformity or unconformity to the underlying rocks.

The Evidence of Unconformities.—The existence of a wide-spread unconformity in any district, accompanied by the absence of certain groups of rocks which occur in neighbouring districts, raises the presumption that the first district was a land tract during the period which these rocks represent. Unconformities are therefore very important guides in the restoration of ancient geographies, because we may regard the eroded surface as the actual relic of an ancient land. It does not, of course, present all the physical features of that ancient land, because the surface has usually been greatly modified as its successive levels came within the erosive powers of the sea under which it afterwards sank. Still we can often tell whether it was originally a high and hilly land, or whether it was of no great elevation.

In drawing inferences, however, from the absence of certain formations above a surface of unconformity, some caution must be exercised. If an unconformity occurs between portions of two systems which are in geological sequence, such as the Ordovician and the Silurian, or between two parts of the same system, we must conclude that the older set of rocks was elevated, and partially converted into land, during the epoch which is represented by the break or gap. The whole of the eroded surface must have been brought within the reach of detritive agencies, though it would not be certain that the whole of it was actually raised into dry land. Again, if a whole system of rocks be absent, we may reasonably suppose that the area in question was land throughout the whole or greater part of the unrepresented period.

If, however, the gap is very great, and several systems of rocks are missing, we must not conclude that the area has been continually above water during the whole of the periods of time which are unrepresented. The area may have been submerged more than once in the interval, and may have received deposits belonging to more than one of the absent systems, but all remnants of these deposits may have been swept away during the erosion which accompanied and followed the last elevation. Thus the Trias rests in many places on Silurian or Devonian rocks, but it is probable that in most of these cases the older rocks had sunk beneath the Carboniferous sea, and had originally been covered with some portion at least of the Carboniferous system; the Dyassic or Permian period, which succeeded the Carboniferous, was one of great disturbance and denudation, and large areas of Carboniferous strata were then broken up and removed, so that the absence of these strata at the localities in question was probably due to this erosion. Such an unconformity may then be evidence of land in Dyassic times, but affords no clue to the position of the land tracts in the Carboniferous period.

Again, in the Lake District of South Cumberland and Westmoreland there are no Secondary rocks later than the Trias, and no Tertiary deposits of earlier date than the Pleistocene, but to infer from this that the district was dry land throughout the whole time represented elsewhere by the Secondary and Tertiary rocks is quite unwarrantable. It may have been submerged several times, and the reason why we do not find any records of these submergences may be that the Mesozoic deposits have been swept off this and most other parts of North Britain during their long exposure to erosive agencies in Tertiary times.

The force of these observations may be better appreciated if we consider the geological structure of that part of Ireland which is nearest to Cumberland. There we have a similar Palæozoic sequence; above which are Triassic deposits, succeeded by remnants of Lias, Greensand, and Chalk, these strata having been preserved by what may be termed a geological accident. This occurrence was the outpouring in Eocene time of a huge sea of basaltic lava which spread over a large part of N.E. Ireland. Covered and protected by the hard basalt, the soft Mesozoic deposits have been preserved to the present day, but we cannot doubt that, if they had not been so protected, the whole of the Chalk, Greensand, and Lias would have been removed from the surface, and probably much of the Trias also. In that case the greater part of Antrim would have resembled the rest of Ireland in having no rocks to represent the periods between the Trias and the Pleistocene.

To the student of ancient geographies, then, the value of an unconformity depends on the number of rock-groups that are absent. Slight unconformities may not be sufficient to indicate the existence of a land surface, while a great gap only proves that the area was land during one or more of the periods which are unrepresented, and collateral evidence is required to determine which periods were those of terrestrial conditions.

A set of beds which overlap each other, each higher bed extending over a wider area than the one below, may be regarded as presenting us with a succession of shore-lines, even although the actual beach deposits have been destroyed during the progressive submergence to which the overlap testifies. It is essential, however, that the nature of overlap should be properly understood, and that it should not be confused with *overstep*, which is the transgression of one rock-group across the outcrops, or basset-surfaces, of an older set of strata. Neither overlap nor overstep can occur without the existence of an unconformity between two formations ; but overlap describes a relation between two parts of the newer formation, while overstep indicates a relation between the lowest bed of the newer series and one or more members of the older series.

It has been stated above that a slight unconformity may not suffice to indicate the existence of a land surface over the tract where it occurs, and it may be well to explain this remark more fully. Let us imagine an uplift taking place in the central part of the North Atlantic Ocean, where a large tract of the floor around the Azore Islands is less than 1000 fathoms deep. If the upheaval was sufficiently rapid or spasmodic to overcome the erosive action of the surface waves and currents, a large part of this region would be converted into land by an uplift of say 5000 feet, but other parts would only have been brought near the surface and would remain as submarine banks which had been continuously worn down by the action of currents and storm-waves.

Let us now suppose that a reverse movement set in and that the whole area subsided gradually through 1000 feet. Fresh deposits would be formed and parts of them would be spread over the submarine banks ; these would lie unconformably on the abraded surface of much older deposits, but without any great discordance, possibly even lying in apparent conformity on the latter, and without any conglomeratic basement bed or other accompaniment of a strong unconformity.

Such a break in continuity would not be very conspicuous, and might even be difficult to detect if its plane were exposed over only a small area, yet there would in most cases be a well-marked plane of erosion or of demarcation, and there would certainly be a great contrast between the fauna of the newer deposits and that of the older. As an actual example of such an unconformity that between the Ordovician and Silurian rocks of Ingleborough and Horton in Yorkshire may be mentioned, for it has been explained by Professor Hughes as having originated exactly in the manner above described.[1]

[1] *Proc. Yorkshire Geol. Soc.* vol. xv. p. 362 (1905).

Conglomerates and Pebble Beds.—All deposits which contain stones or pebbles derived from older rocks afford valuable evidence of another kind, for such stones may be regarded as a collection of rock-specimens obtained from the land which was then exposed to erosion. Even very small pebbles scattered through a sandstone, when sliced and examined under the microscope, are often of much use in showing what kind of rock was being destroyed to furnish the materials of the sandstone.

In many cases the stones which occur in an old conglomerate or pebbly sandstone can be identified with older rocks still existing in the same district, while in other cases they appear to have been brought from some distance. In any case it is obviously a matter of prime importance to examine all such pebbles, and to compare them with the rocks they most resemble in order to ascertain whence they have come. We shall not, indeed, be in possession of all the available evidence until every such pebble bed in the British Islands has been fully investigated. The researches of Dr. Sorby and Professor Bonney show how much information is afforded by this line of research, and also teach us how much still remains to be discovered.

In cases of unconformity the rocks which rest directly upon the old land surface are generally conglomerates or pebbly sandstones, the materials of which have been derived from the rocks of which that land was composed. Such conglomerates often cover very large surfaces, but it is well to remember that such beds are not the invariable accompaniments of unconformity. Thus, where a tract of land has sunk slowly beneath the sea for a long period of time, so that the newer deposits have overlapped one another against its sloping surface, the lower portion of the newer series may be margined by conglomerates, while the higher portion is not; the latter may consist of shales and sandstones, with perhaps barely a foot of pebbly material at their base.

Instances of such overlap with an absence of conglomerates are common in the case of the Carboniferous system; where the Lower Carboniferous rocks lie unconformably on older strata, conglomerates and pebbly sandstones are always present, but where the Coal-measures overlap the lower group, and lie on older beds, they often rest directly on the surface of the latter without the intervention of any conglomerate, and with only a thin pebbly basement bed. So also in the east of England, where an ancient land surface is buried beneath the Cretaceous rocks, the Gault clay overlaps the sandstones and rests on the older rocks with a mere basement bed, which is generally only a foot in thickness. Again, as Professor Bonney informs me, the pebble beds at the base of the Jurassic series of the Alps are very insignificant, and are in many places represented only by a little coarse grit.

When such cases occur we may perhaps infer that the extent and height of the land had been so reduced by continued submergence that the area remaining was small and of low elevation above the sea, so that the conditions were unfavourable for the formation of conglomeratic beds. In many cases the tract of land had doubtless been reduced to the condition of an island, an isthmus, or a low promontory. In other cases much land of high elevation may still have remained above the level of the encroaching sea, but the mouths of the river-valleys having been converted into deep inlets or fiords the rivers would be prevented from carrying pebbles into the open sea. Professor Bonney has informed me that this is the case on the coast of Norway at the present time, few pebble beaches being found along the Norwegian coast.

It must also be remembered that the mere presence of a conglomerate or pebble bed is not of itself a proof of unconformity, for such beds may be interstratified with sandstones, or may rest on what is called a "surface of contemporaneous erosion." In such a case the rock on which the conglomerate rests will belong to the same series of beds, and the phenomenon will only indicate some change in the strength or direction of the currents.

Shallow and Deep Water Deposits.—It is evident that in considering the probable position of shore-lines during any geological period, we must know what kinds of rock are likely to have been formed in shallow water. As a general rule, the coarser the grain of the rock the shallower was the water in which it was formed, and the nearer was the shore from whence the component materials were derived, or along which they were moved.

Outside a continent which has a fairly uniform coast-line trending for a long distance in one direction there is generally a regular succession of deposits from the coast-margin outwards, the coarseness of the materials decreasing with the distance from land, so that we pass from shingle or coarse sand to fine sand, silt, clay, and calcareous mud. But along coasts which have many inlets or bays this order is not so well preserved, and fine silts or muds are sometimes formed quite close inshore ; similar deposits of very fine grain occur also in the estuaries of large rivers. Conglomerates consisting of stones which could only be moved by strong currents, or by the beating of waves on a shore, are, of course, good evidence of the close neighbourhood of land to the spot where we now find them, and if such deposits form a mass of considerable thickness, with large angular or sub-angular boulders, it is probable that much of the material was brought down by floods and torrents from a range of hills above the coast-line.

We must remember, however, that such coarse deposits are not formed everywhere along a line of coast, and that sandstones may have been formed as close to a shore as conglomerates; nay, some sandstones have, doubtless, been formed above high water, and were originally sand-dunes, such as are common on our present coasts.

Sandstones formed from æolian drift, or blown sand, may generally be distinguished from water-borne sands by the character of their component quartz-grains; those of the former being all much worn, rounded, and polished, while in the latter a large proportion of the grains are angular. Professor Daubrée [1] and the late Mr. J. A. Phillips [2] have shown that the wearing down and rounding of angular quartz-grains is an exceedingly slow operation, and that a grain of quartz one-fiftieth of an inch in diameter requires an amount of abrasion equal to that which would result from its having travelled a distance of 3000 miles in water before it becomes so rounded as to assume the form of a miniature pebble. In sand from the seashore of Cornwall Mr. Phillips found that all the quartz-grains between one-twentieth and one-fiftieth of an inch diameter were still angular, although they had been for years exposed to the beating of the waves. Only a few of the larger grains were partially rounded, and the same is the case with the sands of other shores.

Mr. A. R. Hunt has indeed pointed out that on some submerged sand-banks the sand-grains are much more rounded, for the sand accumulated in such places has been rolled and drifted by tidal currents for a long period of time, and is not receiving a constant accession of fresh unworn material like the sand on a shore.

No sea-sand, however, has yet been described which is entirely composed of rounded grains without any admixture of angular or sub-angular particles. The sands of the African and Arabian deserts, on the contrary, consist of completely rounded grains, which, when examined under a microscope, are seen to be miniature pebbles; this condition being due to their long-continued friction against one another under the influence of the wind. The grains of blown sand from English dunes only differ in being rather less completely rounded. Most sandstones consist of more or less angular grains, but beds of consolidated æolian sand exist in some formations; they are not, however, of frequent occurrence, and most of the sandstones met with in the geological series are of

[1] *Géologie expérimentale*, p. 256 *et seq.*
[2] *Quart. Journ. Geol. Soc.* vol. xxxvii. p. 21.

marine origin, and the quartz-grains show various degrees of wear, some being rounded, and many angular or sub-angular.

Pure quartzose sandstones of marine origin are always shallow-water deposits, and are seldom found in deeper water than fifty or sixty fathoms, except where the bottom slopes very steeply from the coast; neither do they generally occur at a greater distance than twenty or thirty miles from land, except in shallow and land-surrounded seas, like the North Sea.

Ripple-marks are features peculiar to sandstones and sandy mudstones, and are often regarded as proof of very shallow water, because of the popular misconception regarding the manner of their formation. We must not, however, suppose that ripple-marks are only produced between tide-marks by the retiring tide; they are caused by any current that has sufficient velocity to move particles of sand on the sea-bottom, and it has been shown that such movement can and does occur at depths of thirty or forty fathoms in the English Channel.

Ripple-mark and current-bedding often afford valuable indications of the directions from which the currents came at the time when the deposits were formed, and thus throw light on the physical geography of the sea at that time.

In a normal sequence of deposits, clays and shales represent deeper water than sandstones, but there are so many exceptions to this rule that it cannot be taken as any guide in dealing with argillaceous deposits. Limestones again were formerly supposed to have always been formed in comparatively deep water at a distance from land, but though certain kinds of limestone are of deep water origin, others, such as coral limestone, are only formed in shallow water, and others again may not even be of organic origin, but may be a chemical precipitate or even a mechanical sediment.

The possibility of some limestones having been mechanically transported sediments has been discussed by Professor W. J. Sollas [1] and by Mr. H. B. Woodward,[2] the latter having argued that most of the Liassic limestones are detrital deposits formed in shallow water. As he remarks, "there are many stratigraphical facts that lead to the conclusion that the Lias limestones were to a considerable extent sedimentary in their character, and that they were derived more or less mechanically from the waste of the older rocks that formed land-areas during the Liassic period. The limestones themselves are for the most part earthy and argillaceous, so that the materials constituting the mass of the Liassic strata might have

[1] *Quart. Journ. Geol. Soc.* vol. xxxv. p. 492, and vol. xxxix. p. 614.

[2] "The Jurassic Rocks of Britain," *Mem. Geol. Survey*, vol. iii. p. 27.

been derived from the waste of Palæozoic limestones and shales; these old rocks being ground into calcareous mud by the breakers on the sea-shore or along the borders of a turbulent estuary. This view is indeed maintained by Messrs. Tate and Blake (*The Yorkshire Lias*, p. 215), who speak of the calcareous portions of the Lias being derived from pre-existing strata, and not directly from organic remains."

Every case in which limestones occur must be dealt with on its own merits, and no hasty conclusion as to the distance of land should be formed. There is, in fact, no rock-name that includes so many varieties as *limestone*, and the conditions under which a limestone may be formed are as numerous as are the varieties. That many of the limestones which occur among British rocks are shallow-water deposits is generally admitted; no one would claim a deep-water origin for a current-bedded oolitic limestone, or for the Llandovery limestones, which succeed sandstones and conglomerates, or for the Liassic limestones of Glamorganshire. The Carboniferous limestones of Northumberland and Scotland can hardly have been deep-water beds; and perhaps none of the Carboniferous limestone, even in its more massive facies, was formed very far from land, though the water was doubtless clear and deep in those places where it attains great thickness.

The only inference that can usually be drawn from the existence of a fairly pure limestone, other than chalk, is that the water below which it was formed was pure and clear. Now to have a clear sea in the neighbourhood of land there must be an absence of mud-bearing streams; if, therefore, we have any reason to suppose that a given limestone was formed near land, we are justified in making certain assumptions with regard to the physical geography of that land; we may, in fact, assume that one of three conditions prevailed—either it was the coast of a land which had a very small rainfall, or the rivers were directed away from that portion of the coast-line, or else it was an island with only few and small streams.

It is now generally acknowledged that the great mass of the rocks which compose our modern continents are such as are now only formed within 200 or 300 miles of land, and very seldom include any deposits which resemble those now accumulating in the depths of the Atlantic and Pacific Oceans. There is only one formation in Britain which was undoubtedly accumulated in deep water at a great distance from land of a *continental character*, and that is the Upper Chalk.

Massive compact limestones and calcareous clays or marls have generally been formed in water of considerable depth. Many bluish and greenish clays, shales and slates, especially such as do not contain many fossils, have doubtless been formed in fairly deep water, and are comparable to the blue and green muds which are found over certain tracts of the sea-bottom, between the shallow water and the deeper tracts of the ocean.

On the other hand, black carbonaceous clays containing much organic matter, and associated with sandstones, would lead us to suspect the neighbourhood of a swampy shore or the estuary of a large river. When, therefore, we have to deal with clays and shales, we must be guided largely by their fossil contents, and by the nature of the other beds with which they are associated, in deciding whether they are shallow or deep water deposits. When we speak of deep-water deposits, it must be remembered that comparatively deep water is meant, not water of oceanic depth.

The Evidence of Organic Remains.—At the present day the creatures which live on the floors of deep oceans are very different from those which live in shallow seas and along the borders of the great continents. It is improbable, however, that this difference has always existed. In the first place, it is by no means certain that the oceans themselves have been in any way permanent, or that the open seas of early periods were anything like so deep as those of the present day. Again, there are good grounds for believing that the specialisation of the modern deep-sea fauna is the result of a long process of migration and adaptation.

It is the opinion of such biologists as Moseley and Heilprin [1] that all the primary branches of invertebrate animal life were developed in shallow water, and that the deep-sea fauna has been derived from the littoral fauna, "not in most remote antiquity, but only after food, derived from the débris of the littoral and terrestrial faunas and floras, became abundant in deep water."

The first inhabitants of deep-water floors were probably animals which were forced to adapt themselves to conditions of greater pressure and less light during a prolonged subsidence of the area in which they originally lived. During this process it is only likely that some would perish and some would survive, and the process of selection has doubtless been repeated again and again during the long ages of geological time. From time to time also these deep-water forms may have been reinforced by species from the shallower waters, which found themselves unfitted to compete with newer immigrants into those areas, and were consequently compelled to migrate into deeper waters.[2]

[1] See Heilprin's *Distribution of Animals*, Internat. Science Series, 1887, p. 126.

[2] The Molluscan genus *Pleurotomaria* is an instance of this, for in Jurassic

When, therefore, we go back to early Palæozoic times it is really improbable that the deepest parts of the seas had any inhabitants at all, except such as lived in the surface waters; and further, that very few species had yet found their way even to the areas beneath moderately deep water. If any difference had begun to show itself, say in Ordovician time, between the assemblages of genera living in shallow water and those of rather deeper water, we can only hope to discover it by comparing the fossil faunas found in different lithological facies of the system.

It is also clear that it must be unsafe to draw conclusions as to the conditions under which any Palæozoic deposit was formed by assuming that the organisms whose fossil remains it contains had the same habits of life as their modern representatives.

There are two groups of animals from the occurrence of which as fossils rash and unsound conclusions have been drawn, and about which I shall here make some observations in order to avoid the necessity of repeating similar remarks in other chapters of this book. These two groups are the Radiolaria (or Polycistina) and the coral-forming Actinozoa.

Radiolaria are minute Protozoa, and many of them construct wonderful siliceous skeletons which form exquisite microscopical objects. These creatures, as might be expected from their low and simple organisation, made their appearance at a very early period of geological time. From their occurrence it has been supposed that the deposits which contain them were of deep-water oceanic origin; probably because the *Challenger* Expedition made it widely known that Radiolarian skeletons are the chief constituent of a deposit found in the deeper parts of modern oceans. It is, however, quite a mistake to suppose that the skeletons of Radiolaria can only be preserved in a deep-sea deposit.

In the first place, Radiolaria exist at all depths of the sea, and in all those parts of the world where the winter temperature of the water is not very low; consequently there is no reason why their remains should not occur in deposits formed at any depth. As a matter of fact they have been found as fossils in deposits of various kinds, including some which were obviously formed in shallow water. Mr. L. Cayeux has described[1] fine arenaceous deposits containing Radiolaria as occurring in the Jurassic and Cretaceous strata of the Ardennes, the beds in both cases being fine glauconitic

times it was abundant in the shallow seas of the European region, but at the present time only a few species survive in depths of from 100 to 200 fathoms.

[1] "Contribution à l'étude des terrains sédim." *Mem. Soc. Géol. Nord*, tom. iv., Lille, 1897, pp. 19, 55, and 129.

sandstones ; also in a similar fine sandstone of Lower Eocene age near Peronne, the rock consisting of fine sand mixed with sponge spicules and tests of Radiolaria, and the whole compacted into a hard stone by a siliceous cement. All these deposits must have been formed in comparatively shallow but clear water.

Again Mr. Coomáraswámy has recorded the occurrence of Radiolaria in the Gondwana Beds near Madras, and remarks :[1] "The association of these Radiolarian forms with plant-remains is of great interest, as the shales must have been deposited in *comparatively* shallow water, a state of things also indicated by the detrital character of the other beds included in the Sripermatúr group." These shales have a porcellanic character from the abundance of the Radiolarian tests, though they do not possess quite the hardness of chert. Mr. Foote considers that they were formed in tranquil water at a sufficient depth to be beyond the agitation of the waves, and they are actually associated with remains of plants which must have been drifted out to sea from the neighbouring land. Here, therefore, we have proof that a Radiolarian chert or porcellanite can be formed in water of no great depth and at no great distance from land.

Remains of Radiolaria are found in many deposits of Palæozoic age, and in all the cases hitherto described they occur in nodules or layers of chert which are embedded in dark grey or black shales. Such Radiolarian cherts have been found in Ordovician, Silurian, and Carboniferous rocks ; those of the older Palæozoic systems being often associated with shales containing Graptolites. They generally occur in districts where the sedimentation was slow, and where the total thickness of deposit is small ; and in such cases they may be taken to indicate areas of deposition which lay at a considerable distance from land.

Lithologically, however, the shales which enclose the cherts bear no resemblance to the Radiolarian ooze of modern ocean-abysses, nor to the white Radiolarian earths of Barbados, in which chert-nodules actually occur. The material of the black shales seems to be largely of terrigenous origin, those of Carboniferous age in Devon consisting mainly of fine particles of quartz and mica. The black matter by which they are coloured is probably some bituminous hydrocarbon, which may be either of animal or vegetable origin, and is possibly in some cases due to the decomposition of the soft parts of the Radiolaria or of Graptolites.

Such shales are comparable rather with the blue muds of modern seas than with any kind of oceanic deposit. Blue muds generally occur only in the neighbourhood of land and within a depth of

[1] *Geol. Mag.* 1902, p. 306.

200 fathoms, but where large rivers empty great volumes of mud into the sea such muds may extend to a great distance from land, and to depths of over 1500 fathoms, as in the cases of the Arabian Sea and the Bay of Bengal. In Palæozoic times blue and black muds may have extended to equal distances from land, but it does not follow that the seas were anywhere so deep as 1500 fathoms.

We may therefore accept a condensed Radiolarian and Graptolitic facies of a formation as indicating deposition at a considerable distance from land and a proportional depth of water, but not as a deposit in any way comparable with the Radiolarian ooze of modern ocean-depths.

The other group of fossils from which some rash conclusions have been drawn are the Actinozoa (Corals). The families to which modern reef-building corals belong do not date back beyond the beginning of Mesozoic time (Triassic period); while the Palæozoic corals belong to the subdivisions known as the Tabulata and the Rugosa, both of which are entirely extinct. Consequently we have no information about the habits and life-history of these groups beyond what can be inferred from their mode of occurrence as fossils. Other genera, usually called Corals, such as *Heliolites*, are now believed to be Alcyonarians.

These Palæozoic forms of Actinozoa became rare at the very time when the Madreporaria, to which order the modern reef-building corals belong, became the dominant group. Hence it is clear that the mere abundance of corals in a Palæozoic limestone is no proof that such a limestone formed part of an ancient coral-reef. Yet it has often been asserted that certain masses of limestone are coral-reefs, merely because they are *coralliferous* limestones; moreover, mere beds of coralliferous limestone a few feet in thickness have been called "reefs" by people who have never seen a real coral-reef, and do not know what reef-rock looks like.

Such beds of coralliferous limestone have probably been formed in the same way as those of crinoidal limestone, that is, they are tracts of an old sea-floor on which colonies of corals grew and flourished, died and fell to pieces until their remains accumulated to form a continuous layer of several feet in depth. Such beds are sometimes actually interbedded with crinoidal limestones, as is notably the case in the Devonian limestone near Torquay, and it is evident that they only represent episodes when the prevailing growth of Crinoids was replaced for a time by a growth of corals.

Even in dealing with Mesozoic limestones, caution should be used in coming to the conclusion that some particular coralliferous limestone is an old coral-reef. I imagine that a real fossil coral-reef should not only be an isolated mass of such limestone, but should, if perfect, have one very steep or wall-like side, this side being bordered by a fine-grained marly or chalky limestone, of similar composition to the calcareous mud found outside modern coral-reefs. The rock itself must be entirely massive and unstratified, containing large pieces of compound corals in the position of growth, held together by the surrounding mass or matrix of broken corals, shells, and other organic remains. The proportions of more or less perfect coral-growths to the detrital matrix will vary in different parts of the reef rock, according as they were near the inner or the outer parts of the original coral-reef.

Variations in Thickness.—The evidence derivable from the thinning and thickening of deposits also merits some examination. If we consider the case of sediment which is being transported by the action of a current setting off a coast-line, there can be little doubt that the greatest amount of sediment would be thrown down at a certain distance from land, where the bottom began to shelve into deep water. Little could be deposited in the shallow water near shore, but would be carried to a greater or less distance in proportion to the depth of the water ; and if the bottom shelved gradually the deposit might cover a considerable space, but as soon as fairly deep water was reached most of the sediment would subside, and little would be left to travel farther. A deposit formed under these conditions would form a large lenticular mass which would thin out principally in two directions, viz. in the direction of open sea and in the direction of land. Subsidence would make no difference to this arrangement, but would only tend to increase the thickness of the deposit.

The deposit would also thin out laterally, away from the central axis of deposition, but a transverse section across the mass would exhibit a different appearance from a longitudinal section running parallel to the course of the current. In a transverse section the size and nature of the particles composing the deposit would be nearly the same throughout, while in the longitudinal section we should find a gradation from coarse sand to fine mud.

When, therefore, we are dealing with a deposit or a group of beds which is thinning out in a certain direction, no conclusion should be drawn without having regard to the lithological characters, and whether these change in that direction or not. Thus, if we start with a thick mass of shale or clay, the materials of which must have been derived from the land, and we find that this simply becomes thinner without change of character or replacement by other deposits, we can only infer that we are passing away from the source of supply, possibly toward what was deep water, but more probably in a lateral direction from the major axis of deposition. If, however, as it diminishes in thickness it becomes decidedly more calcareous, assuming the character of a marl and including beds of limestone, we may assume that we are proceeding away from the contemporaneous land and toward what was then an area of clear and deep water.

If, on the other hand, a thick argillaceous deposit is gradually replaced by beds of sandstone, and these by pebbly and conglomeratic beds, there can be no doubt that the position of the contemporaneous land is indicated by the direction in which the coarser beds set in, and that if we could trace the beds far enough they would thin in that direction. Again, if we start with a mingled series of sandstones and shales, and we find that the sandstones thin out in one direction, and that, though the shales may thicken, the whole group thins, we may infer that we are tracing the group away from the source of its material.

We may note here that the formation is likely to be thickest along the tract where shales and sandstones alternate with each other, and as sandstones are more rapidly accumulated than clays, the formation may thicken landwards by the intercalation of sandstones ; so that, if only this portion of a group of beds is preserved to us, the direction of the land will be indicated by the thickening of the sandstones and the thinning of the shales. Among the Palæozoic rocks this is sometimes the only kind of evidence we possess to guide us toward the position of the land areas.

The Difficulties of Geographical Restoration.— These arise chiefly from two causes — the imperfection of our knowledge and the imperfection of the geological record. The first is being gradually removed by the industry of geologists ; but there are still many parts of the British Islands about the geological structure of which we really know very little, and there are many others about which more detailed information is much to be desired. Again, there are very large areas where the older rocks exist, but where they are buried and concealed from view by the newer formations. Thus we hardly know anything of the subterranean geology of the large areas which are covered by strata of Carboniferous age both in England and Ireland. Other areas again are concealed by the Neozoic strata, and we are only just beginning to obtain some knowledge of the underground limits of the older Neozoic rocks by means of the deep borings which have been made from time to time in the eastern part of England.

The imperfection of the geological record is another great source of difficulty, and one which will never be altogether overcome. The rocks which remain to us as the records of any one period are but a remnant of the deposits which were formed during that period, and yet before we can attempt to restore the geography of that time we must replace in imagination the rocks which are lost, so as to form a conception of the space over which they originally extended. For some portions of the space this may be easily done, as in the case of conformable beds lying on each side of an anticlinal, but when the final limit of a formation toward a given direction is a fault or an abrupt boundary, without even an outlier beyond, we are left in complete uncertainty as to the original limits of those beds in that direction. Under such circumstances we are obliged to fall back on general considerations, such as the lithological changes seen in the exposed areas, and the physical characters of the country beyond the present boundary of the formation.

Tectonic and Original Basins.—In connection with this part of the subject there is a point of some importance on which English and French lines of thought are not yet in complete accord: this is a proper discrimination between original areas of deposition and the tectonic basins or centroclines which have been formed by local flexuring of the earth's crust.

In England it has always been held, at any rate since the teaching of Ramsay and Jukes, which dates from 1863, that tectonic basins and synclinal troughs have been produced by subsequent flexuring, and have no direct relation to the original areas of deposition. Thus where several synclinal and anticlinal flexures are parallel to one another, we have assumed that the strata which come into the synclines, but are absent over the anticlines, were originally continuous over the latter; their absence being due to subsequent erosion and denudation. Even where the flexures are of a much broader and more complex description, so as to form large geotectonic basins and anticlines, the English school believes that the newer beds of the geo-syncline were probably continuous over the neighbouring geo-anticline, unless any definite evidence to the contrary exists.

Thus few doubt that the Coal-measures of Lancashire and North Staffordshire were originally continuous with those of Derbyshire and Yorkshire, and that the connecting portions of these measures have been removed from the intervening anticline of the Pennine Hills. It is, in fact, the general belief that the large more or less basin-shaped depressions, which contain the Coal-measures on each side of the Pennine range, have been produced by the intersection of two sets of flexures, the one set running from north to south, and the other set from west to east.

In France and Belgium, however, these views have only been partially accepted. In those countries geologists have been reluctant to admit the probability of strata having extended for any great distance beyond the limits of a basin or syncline, unless some outliers occur to prove such extension. They still show an inclination to suppose that the synclinal troughs to which certain formations are confined are more or less coincident with the areas in which these strata were deposited.

Some have supposed, for instance, that the synclines in which the Devonian and Carboniferous rocks of the Ardennes are found indicate not only the general trend of the Devonian coast-lines, but that the extreme northern and southern boundaries of these rocks were also the approximate limits both of the Devonian and Carboniferous seas. The same assumption has been made in the case of the synclines to which the Carboniferous rocks are restricted in Brittany.

The consequence is that some French restorations of Palæozoic geographies exhibit long narrow tracts of land and sea, which have a curious parallelism and an improbable appearance about them; seeming, in fact, to show a minimum of sea with a maximum of land, while perhaps we may admit that English geologists deem it safer to show a maximum of sea with a minimum of land.

In any case an anticline must not be taken as prima facie evidence of the existence of land, and the strata which occur within a synclinal trough or basin should be considered in exactly the same way as if they were horizontal or inclined in one direction.

Thus it may happen that certain beds are actually overlapped by others within the limits of a broad syncline, and in that case we should infer that a shore-line was intersected where the overlap was found to occur.

Again, in crossing a syncline beds may change their lithological characters, and some particular group of beds may change from a set of alternating sandstones and shales to massive sandstones with occasional layers of coarse sand or conglomerate. In such a case one would of course infer that land had lain in the direction toward which the deposit became coarser in grain, but the shore of that land may have lain far beyond the present boundary of the coarse sandstone within the syncline.

I am far from denying that there are cases in which the interpretation of the stratigraphical facts becomes difficult; for if fossils are rare or non-existent in certain beds, it is not always easy to correlate the succession of strata which occur on the opposite sides of a syncline or in two synclinal troughs which are separated by an anticlinal ridge, consisting perhaps of very much older rocks than those which overlie it and are partially preserved in the synclines. All that I desire to urge is that the tectonic structure must be ignored, and the evidence of the strata themselves considered exactly as if the flexures did not exist.

No doubt there are areas which can be truly called "basins of deposition," both lacustrine and marine, in which the successive deposits overlap one another in all directions, and the boundaries of which are generally irregular. Such basins can often be traced among Neozoic rocks, but seldom among the more disturbed and flexured older rocks. Sometimes, again, basins are partly tectonic and partly of surface origin; thus the Paris basin, so far as the Eocene Beds are concerned, is part of a basin of deposition, but it was not a basin in Cretaceous times, though tracts of land then existed to the west, south, and east of it. In its present form, it is a tectonic basin produced by post-Eocene movements.

Having above indicated some of the difficulties with which the student of Palæogeography has to contend, I must ask my readers to remember that the further we go back into past time the less information, as a rule, do we possess about the facts which should guide us in restoring the geography of any particular region, such as that of the British Isles. Hence some of the restorations attempted in the following chapters, especially those of the earlier periods, must be regarded as tentative arrangements of land and water, constructed in accordance with the evidence at present available, but liable to modification in the future as a consequence of fresh discoveries.

In some instances the known facts suggest different inferences to different minds, and there are several cases in which divergent views have been held with regard to the conditions under which certain deposits were accumulated. In such cases I have carefully examined the reasons given for the different views, before selecting that which appeared to be the most natural inference from all the facts on record.

CHAPTER II

THE ARCHÆAN ROCKS

SINCE the last edition of this book was issued some of the areas where the oldest known rocks are exposed, both in this country and on the continent of Europe, have been more fully explored and described. Until recently it has been customary to include all these ancient rocks under the indefinite names of Archæan or pre-Cambrian, but the progress of knowledge has made it clear that they include a very great thickness of stratified rocks as well as of crystalline schists and gneisses ; further, that they are divisible into at least two great series or systems, which are separated, at any rate in some regions, by a very distinct break with a marked unconformity.

These primitive formations cannot be classified and correlated in the same way as the Cambrian and all later sedimentary systems can, because they are almost unfossiliferous, only a few doubtful fragments and impressions of what seem to be organic remains having yet been found even in the later and less altered sediments. Consequently even when a succession of pre-Cambrian rocks has been made out in this or in any other country, it is very difficult to correlate the divisions observable in one district with those which can be made in another. At present, therefore, the rock-groups which have been recognised in different localities are known by different local names, so that almost every district, as well as every country, may be said to have its own pre-Cambrian nomenclature.

Again, authorities differ as to the number of distinct rock-groups which can be recognised in the pre-Cambrian areas, as to the inclusion or exclusion of some rock-masses, and as to the relative age of others. There are also differences of opinion as to the precise manner in which some crystalline schists have acquired their present mineral structure.

In these circumstances I have sought the aid and advice of my friend and former tutor Professor Bonney, who has specially studied these ancient rocks not only in England, Wales, and Scotland, but also in France, Switzerland, Norway, and Canada, and has, during the past thirty years, written much concerning their variations in structure, and their relative ages. To him, therefore, I have looked for guidance in the difficult but necessary task of trying to ascertain the probable relative positions of these primitive formations, and of adopting or formulating some definite classification of them.

Professor Bonney believes that not only can the pre-Cambrian rocks be divided into two distinct systems, but that practically all the crystalline schists belong to the older division, so that these two divisions might be described as the uncrystalline and the crystalline. Moreover, he is of opinion that the crystalline division is itself divisible into an older and a newer series separated probably, at any rate in some regions, by another break and unconformity.

Some writers have advocated the restriction of the term *Archæan* to the oldest of these three divisions, *i.e.* to the ancient gneisses which seem to be the fundamental rocks underlying all other recognisable rock-groups both in Europe and in America. The name has, however, been more generally used to designate all the rocks which are older than the Cambrian, in fact as a substitute for the term pre-Cambrian, which is a convenient adjective, but a bad name for a system or an era.

If used in the wider sense the *Archæan* represents an era, comparable with Palæozoic, Mesozoic, etc., and can then be divided into as many systems as may eventually be found necessary. Professor Bonney suggests the following arrangement of the Archæan rocks:—

3. Eparchæan — Various sediments with local volcanic rocks, comparatively unaltered, Pebidian, Charnian, Torridonian.

Break and Unconformity.

2. Mesarchæan—Schists and schistose rocks, largely of fragmental and sedimentary origin.

Break and Unconformity.

1. Protarchæan—Gneisses and schists, largely of igneous origin.

This scheme has the advantage of being applicable to the whole of Europe.

1. The Protarchæan System

I have, therefore, to commence my story by giving some account of what are really the foundation stones of the British

Isles; rocks which can be seen to underlie the oldest stratified deposits in our country, and rocks which may reasonably be supposed to form a kind of fundamental platform below the whole of the British region. Moreover, they are not only the oldest British rocks, but are believed to be as old as any on the continent of Europe, where similar fundamental masses crop out in several places and form isolated tracts, such as those of Scandinavia, Saxony, Bohemia, Switzerland, Baden (Black Forest), the Pyrenees, and Brittany.

Our islands are, of course, but a fragment of Western Europe, and it might have been expected that they would prove to have been built up on the same foundation; but the actual exposure of this foundation in several parts of the British area is a fortunate circumstance, which enables us to begin at the very beginning of the "Building of the British Isles."

These primitive rocks have been called *Hebridean* and *Lewisian* from their typical exposures in the cliffs of the Hebrides and of the N.W. of Scotland; similar rocks have been found in the N.W. of Ireland, in Anglesey, in Shropshire, and in the Malvern Hills. It is unnecessary to burden these pages with detailed descriptions of them, and it will suffice to mention such facts about those of Ross and Sutherland as will make their relative age and composition clear to the reader.

The Hebridian complex of the N.W. of Scotland (see map, Fig. 1) is described as comprising three different components: (*a*) gneisses which have affinities with plutonic igneous rocks in their mineral composition; (*b*) intrusive igneous rocks, both acid and basic, which penetrate the gneisses; (*c*) crystalline schists and limestones which seem to be altered sedimentary rocks; but these last are restricted to areas about Gairloch and Loch Maree.

"Along the western seaboard of the counties of Sutherland and Ross the Lewisian or fundamental gneiss forms an interrupted belt stretching from Cape Wrath to Loch Torridon, and thence to the islands of Rona and Raasay. Throughout this belt of country bare rounded domes and ridges of rock, with intervening hollows, follow each other in endless succession, forming a singularly sterile tract where the naked rock is but little concealed under superficial deposits, and where the surface is dotted over with innumerable lakes and tarns."[1]

But though the physical aspect of the country is uniform, the component rock has a complex structure, consisting mainly of material which has the crystalline banded and foliated structure

[1] "The Geological Structure of the N.W. Highlands of Scotland," *Mem. Geol. Survey*, 1907, p. 1.

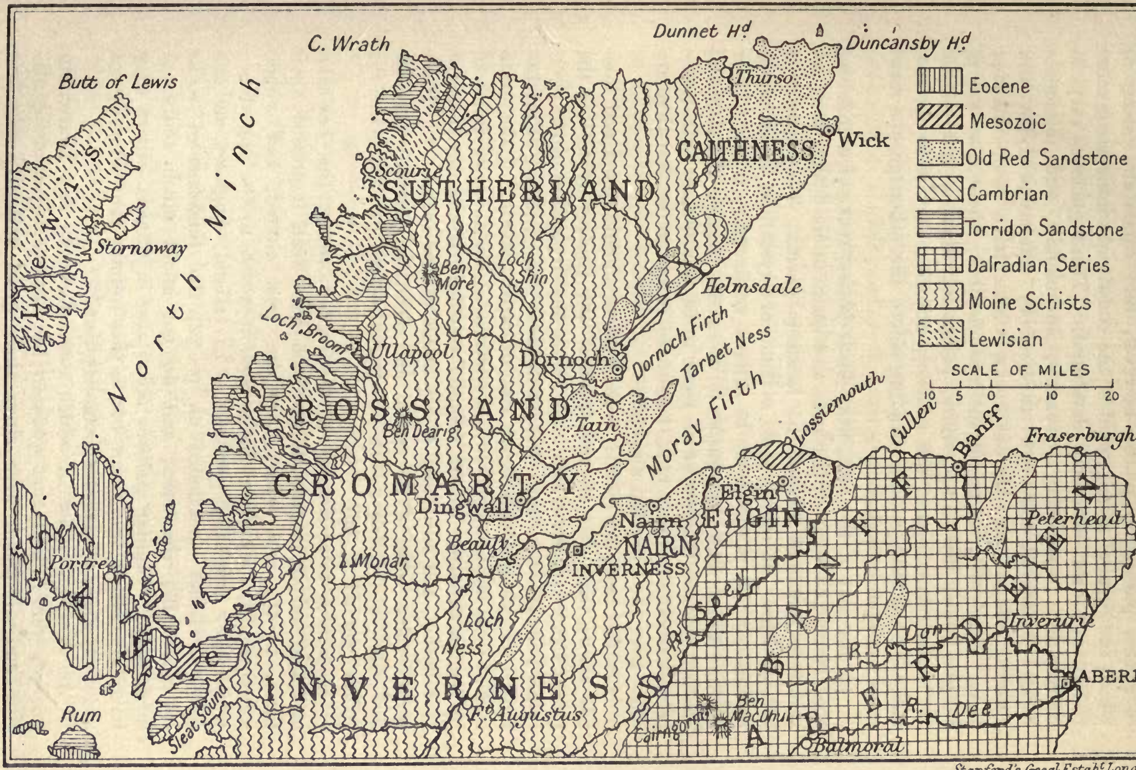


Fig. 1.—GEOLOGICAL MAP OF THE NORTHERN PART OF SCOTLAND.

of gneiss, passing in places, however, into bands and bosses in which the parallel arrangement of the constituent minerals is more rudely and even obscurely developed. These gneisses vary in composition, comprising pyroxenic, hornblendic, and micaceous rocks. Moreover, they are traversed by numerous dykes and veins of indubitable igneous rocks, which have been intruded along more or less highly-inclined fissures; these also are of various kinds, including granite, pegmatite, diabase, and picrite. It is also evident that the gneisses, however they were formed, had acquired their mineral banding before the other igneous rocks were intruded into them.

In one part of the area, near Loch Maree, rocks of a different character make their appearance and seem to lie within a broad and deep synclinal fold of the Lewisian gneiss. They consist of several kinds of schist with a band of crystalline limestone or marble, and they appear to be altered sedimentary rocks. Their relation to the Lewisian gneiss is uncertain because the planes of contact between the two series seem to be shear-planes with bands of mylonised (crushed) rock, but there is no doubt that they are older than the Torridon sandstone.

Detailed mapping of the western parts of Sutherland and Ross has shown that after the intrusion of the igneous dykes into the pre-existing rock-mass, and long before the deposition of the overlying Torridon sandstone, the whole area was subjected to intense lateral pressures, which "gave rise to rapid plication of the strata and to lines of disruption or shear-zones, accompanied or followed by recrystallisation of the original constituents, the development of foliation, and occasional mylonisation of the rocks. . . . These pre-Torridon lines of disruption and shearing generally run east and west, or W.N.W., that is, approximately parallel with the dykes" (*op. cit.* p. 36).

Such is a brief account of the rocks forming the Lewisian complex, and of the structures which have been impressed upon them, in the area where they are least altered, and where, consequently, they show the nearest approach to the appearance which they originally presented. In Ireland, Anglesey, and the other localities mentioned on p. 22, the fundamental rocks exhibit similar characters, and do not afford much additional information. Similar gneisses occur also in Canada, where they have been called *Laurentian*, but in that country they often do not show any signs of pressure metamorphism.

As to the manner in which these Lewisian and Laurentian gneisses were formed, that question has been a subject of speculation and discussion ever since their great antiquity was first recognised. One early and very natural view was that they were portions of the first crust that was formed on the surface of the earth as it cooled down from a state of liquefaction. As a result of much observation, discussion, and controversy, it is now generally admitted that these most ancient gneisses consist largely of igneous rocks like granite, syenite, and diorite, and further, that some portions of the mass seem to have been intruded into other portions, a conclusion which leaves the origin of this earlier portion still in doubt; for if some parts of these gneisses were intrusive plutonic rocks they must have been intruded into some pre-existent consolidated rock-masses, and must in reality be younger and newer than those rock-masses.

Here a distinction must be drawn between typical Protarchæan gneisses and the granitoid gneisses which often penetrate the newer gneissic and schistose rocks. The foliation of the latter is very often nothing more than a rude arrangement of the component minerals in more or less parallel planes, and it is now generally admitted that such structure has in most cases been produced by pressure carried to the extent of a crushing and shearing stress; in other words, to dynamic metamorphism.

The older gneisses, however, exhibit some special characteristics which, in the opinion of Professor Bonney and other geologists, could not be produced by pressure. Moreover, these characters are conspicuous in districts where there is an absence of thrust-planes and the other concomitants of intense lateral pressures. Such gneisses exhibit a marked tendency to the "banded" structure, *i.e.* to a construction in the form of alternating layers of different mineral composition, these layers varying in thickness from a few inches to several feet. It is believed that such banded gneisses could only be formed in two ways: either by the injection of one igneous rock into another, which was so softened that a fluxion-structure was set up in both rocks before the final crystallisation; or else by extreme alteration and recrystallisation of sedimentary rocks.

Probably some kinds of banded gneiss have been formed in one way and some in another. Thus the banded gneisses of Sark and of Cornwall seem to have resulted from the imperfect mixture of two kinds of igneous rock, the later injection having so softened the other that it was made to flow slowly with the more liquid material. On the other hand, there are cases where banded gneiss occurs in association with crystalline limestone or calc-mica schist, and the banding of the gneiss is parallel to the bedding-planes of the other rock, leading to the inference that the whole was originally a series of stratified materials. It does not follow, however, that the conditions under which such rocks were accumulated and stratified bore much resemblance to those now regulating the processes of sedimentation.

2. The Mesarchæan System

As stated on p. 21, it is very probable that the crystalline schists which overlie the fundamental gneisses are divisible into two distinct groups or systems—a lower group associated with and invaded by the underlying gneisses, and an upper group or *Mesarchœan*, which often lies unconformably upon the former. Probably both these series are represented in the British Isles, but as they have not yet been separated from one another, it is only possible at present to treat the crystalline schists as a whole, and to indicate the areas where they occur.

Reference to any geological map of Scotland will show the reader that the Northern and Central Highlands are chiefly composed of such rocks. This great schistose series of the Scottish Highlands is, however, a complex, including parts of several systems of rocks. It is an area of regional metamorphism, and, while some of the granulitic schists may have been formed by the dynamic alteration of Torridon sandstones, it is almost certain that the complex includes rocks of pre-Torridonian age, as well as some of Cambrian, and possibly others of even later date.

In the Northern Highlands, east of the belt of country described on p. 22, there is a narrow but nearly continuous band of Cambrian rocks (see Fig. 1), and east of this again is a wide region in which the rocks have been faulted, folded, dislocated and overthrust in great slices, one beyond another, so that for a long time their true relations were misunderstood.

The thrusting force came from the E.S.E., and among other results it produced thrust-planes along which great slices of displaced rock were carried bodily over the masses of rock beneath them. The most easterly and most powerful of these displacements has been called the "Moine Thrust." To the west of this line of thrust the rock-masses are simply displaced portions of the Lewisian gneiss and of the two formations which lie upon it (the Torridonian and the Cambrian), and are easily recognisable as such ; but east of the Moine thrust the rock-materials have been so completely altered, crushed, and recrystallised that for many years it was supposed that the eastern gneisses and schists were part of a fourth successive formation, of later age than the Cambrian.

The detailed work of the Geological Survey, as recorded in the "Summaries of Progress" from 1898 to 1908, has resulted in several important conclusions: (1) That throughout the eastern parts of Sutherland and Ross, and in Inverness west of the Great Glen, two distinct groups can be distinguished in the eastern gneisses and schists, viz. A, infolded and inlying portions of Lewisian gneiss; and B, gneisses and schists of a different type, to which the name of "Moine Schists" has been given. (2) That with the Lewisian gneiss is associated a series of altered sedimentary rocks comparable to those of Loch Maree. (3) That the Moine complex can also be separated into two rock-groups of different composition—*a*, granulites or quartzose schists, and *b*, argillaceous or micaceous gneiss (containing both muscovite and biotite micas). (4) Lastly, that the rocks of the Moine complex appear in several places to be unconformable to those of the Lewisian complex.

We must now pass to the great region of the Central Highlands, which extends from the coasts of Banff, Aberdeen, and Kincardine, through the Grampian Mountains to the south-western extremity of Argyleshire in Cantire and the Isle of Islay. This area consists mainly of crystalline schists and of other more or less schistose rocks, which are evidently altered sediments.[1]

The mapping of this large area has been in progress for many years, and though no complete account of it has yet been published, many parts of it have been described in the Geological Survey "Summaries of Progress." Thus it is now known that the Moine schists, both of the quartzose flagstone and the micaceous gneiss types, extend not only to the line of the Great Glen, but across it and through eastern Argyle and Inverness as far as Loch Ericht and the upper part of Strathspey.

South-east of those districts, however, another and very different series of schists has been found to prevail, though here and there a tract of the Moine schists recurs within the area of the other type, as in the Glen Tilt district of Perthshire. The components of this second series are more varied, and some of them are more obviously of sedimentary origin. The chronological sequence of this series has not yet been definitely determined, nor has its relation to the Moine series been ascertained, though in places it seems to lie on an eroded surface of the latter. The line of division on the map (Fig. 1) is only intended to separate the area in which this newer series is found from that in which the Moine schists prevail.

[1] The area also includes many large intrusive masses of true granite, round which the rocks are still more highly metamorphosed; these granites have been omitted on the small map (Fig. 1) for the sake of clearness.

The former comprises a great variety of rocks—mica-schist, quartz-schist, chloritic and sericitic schists, quartzites, grits and conglomerates, limestones and shales,—yet they can be arranged in groups which maintain a certain definite sequence throughout the whole area. The rocks are folded and plicated into a series of major and minor isoclinal flexures, by which the component members of the series are probably reduplicated many times, and the original chronological sequence has not yet been recovered out of this complicated succession of beds.

All that can be said with safety at present is that the strike of this schistose series keeps the same general direction across Scotland for more than 200 miles, and that the same belts of quartzite and limestone are traceable almost continuously across the whole distance; further, that over large tracts the angles of inclination are so low that the beds can be followed along the slopes from hill to hill, almost as easily as the beds of Carboniferous limestone and sandstone are traced along the fells of Yorkshire. Lastly, there is good reason to believe that one part of the series is unconformable to the other part, and has a conglomerate or pebbly bed at its base.

One other special feature has been pointed out by Sir Archibald Geikie, namely, that one of the most persistent horizons in the series is a zone of green schists, coloured by the large proportion of actinolite and chlorite which they contain. He believes that these minerals represent the pyroxenic material of volcanic ash and dust, and that they indicate a time when volcanic action was prevalent over the whole area, or, at any rate, when great eruptions took place, during which immense quantities of volcanic dust were showered out and spread over the area of sedimentation, so as to be incorporated with the contemporaneous deposits.

As these green schists are strongly foliated and are associated with garnetiferous mica-schist and schistose grits, they probably belong to the crystalline Mesarchæan series, and not to any later group which may be included in the complex.

Again, in the north-west of Ireland the tracts of granitoid gneiss mentioned on p. 22 are flanked by large areas of crystalline schists which strikingly resemble those of the Scottish Highlands, so that Sir A. Geikie has remarked: "The Irish development of these rocks is similar to their grouping in Scotland, some of the bands of quartzite, conglomerate, limestone, phyllite, and mica-schist being probably continuations of similar bands on the Scottish mainland, and in the islands of Argyleshire."[1]

These schistose rocks extend southward through Donegal into

[1] *Text-book of Geology*, 4th Edition, 1903, p. 894.

Tyrone, where one or both of them is underlain by a volcanic series consisting of green schists, tuffs, and lavas with a coarse basal agglomerate resting unconformably upon the Protarchæan gneiss. In Mayo, again, there is another large area of crystalline schists; and in the island of Achill a basal conglomerate with a schistose matrix, succeeded by a schistose series of rocks, can be seen resting unconformably upon the older gneiss.

It does not follow, however, that the most ancient portions of the schistose series are involved in these unconformities. Further investigation is required to ascertain whether or not there is a break in the succession of schists corresponding to the unconformity observed in Achill and Tyrone.

It only remains to be mentioned that crystalline schists occur in Anglesey, in the south of Cornwall (Lizard district), and in the southern promontory of Devonshire (Start Point, etc.), but have not been found in any other parts of England or Wales.

With regard to the conditions under which the crystalline schists were formed there is much difference of opinion, and the problem is one in which there is more scope for the imagination than for inductive reasoning. Dr. Sterry Hunt imagined that some of them originated as chemical sediments in seas of hot water after the formation of a sufficiently solid crust on the cooling globe. Another view is that they were sediments of an ordinary kind which have been changed into foliated crystalline rocks by the metamorphic agencies of heat and pressure.

Lastly, it has been pointed out that some hornblendic schists have been formed by the dynamic metamorphism of basic igneous rocks, such as dolerite and diabase; also that some micaceous schists and some epidote schists were very probably clastic rocks of volcanic origin, *i.e.* beds of volcanic dust and ashes which were interstratified with contemporaneous sediments and lava-flows.

The question of original formation is further complicated by the probability that in some and perhaps in many districts there is a *double foliation*. Thus Professor Bonney has pointed out that the gneisses of the Aberdeenshire coast north of Stonehaven show traces of a pre-existent foliation before the rock was subjected to the pressure which has produced the dominant planes of what may be called the cleavage-foliation. In this and in other similar cases the planes of the earlier foliation are parallel to what seem to be the bedding-planes of the whole series, and where limestones are included it is parallel to the surfaces of the limestone beds.

While it cannot be denied that some crystalline schists, both among the older and the newer series, are most probably of the nature of ordinary deposits altered by the combined effects of pressure and heat; it may reasonably be held that the older series of gneisses and schists were formed under a set of conditions which have never recurred during the subsequent history of the earth, because they are so purely crystalline and so different from any recognisable Palæozoic rocks which occur in the same regions. This is Professor Bonney's opinion, but precisely what these conditions were the evidence at present available does not enable us to understand.

All that can be said is that if our globe has cooled and solidified from a state of liquefaction by the radiation of heat into space, there must have been a phase when conditions were very different from those which now prevail. It is not difficult to realise that, for a long time after the formation of a solid crust, and after the surface was cool enough for the condensation of water, the crust would still be comparatively so thin that volcanic phenomena would be almost universal and eruptions more continuous than they are now; movements of the earth's crust would also be more frequent and more extensive. At the same time all the surface phenomena would be very different; bare rocks, unprotected by any soil or vegetation, would be subject to rapid erosion, deposits would be more quickly accumulated. The surface waters too might be warm, and chemical agencies would be more largely concerned in the construction of rocks.

3. The Eparchæan System

We now come to the rock-groups which are known to lie above the older Archæan gneisses and schists, but below the fossiliferous beds which form the base of the Cambrian system. Having been deeply buried in the earth's crust and subjected to much lateral pressure they are generally so far altered that the beds of finer grain exhibit the cleavage of slates or even the still further stage of phyllites, while the arenaceous beds have been compacted into grauwackes and hard grits or quartzites.

As stated in the previous section, it is possible that in some regions the metamorphism of these rocks has been carried still further, and that they have been converted into crystalline schists which have not yet been separated and distinguished from the Mesarchæan schists. At present, therefore, we are only able to deal with those areas where the Eparchæan rocks are comparatively unaltered, and where their original lithological characters can easily be recognised.

Again, we still have much to learn with regard to the stratigraphical succession of these rocks, for they only occur in isolated areas, and it is not yet certain which is the oldest and which is the newest group. Many of the rocks are clearly of the nature of ordinary detrital sediments, while others consist mainly or largely of volcanic debris ; and it is of course possible that the sediments of one are contemporaneous with the volcanic materials of another area. There is, however, some reason for thinking that the oldest group consists mainly of slates, and that most of the volcanic accumulations occupy an intermediate position between the lower slates and an upper set of sedimentary beds.

For our present purpose it will suffice to give a very brief account of the rocks found in the principal Eparchæan areas, and afterwards to indicate such inferences as may be drawn from the facts regarding the conditions under which these rocks were formed. The chief areas where they are exposed are Brittany, Shropshire, Pembrokeshire, Carnarvonshire, Charnwood, and the N.W. of Scotland.

A. *Stratigraphical Evidence*

1. Brittany.—This area, though now part of France, is geologically a continuation of the Cornubian peninsula, to which it was united through long periods of time. Moreover, Eparchæan rocks occupy large parts of Brittany and of Western Normandy, and their relations to the Cambrian rocks above and the older Archæan below is clear and well established, so that they form to some extent a standard of comparison for other areas.

By French geologists this system is known as the Brioverian, from the ancient name of the town of St. Lo in Normandy. In Central Brittany, where the series is most complete, the following descending succession has been made out by Professor Barrois :—

3. Green flagstones and slates with a bed of conglomerate.
2. Green slates with a bed of limestone.
1. Green silky slates or phyllades with black cherts.

The whole has an apparent thickness of 5 kilometres, about 17,500 feet, though there is no definite base-line, but apparently a gradual passage into crystalline schists (? Mesarchæan). No fossils have been found in them except microscopical bodies, some of which appear to be Radiolaria, while others are regarded as Foraminifera.

In the north of Brittany there is a similar slaty series, but it includes a greater variety of lithologic types, including beds of quartziferous slate and of white micaceous quartzite, with a great mass of porphyrites and porphyritic tuffs, apparently over 3000 feet thick, and indicating an episode of contemporaneous volcanic activity.

2. Shropshire.—One of the largest tracts of Archæan rocks in England is that of the Longmynd, which is from 10 to 12 miles long and about 6 miles wide in its broadest part. This area consists for the most part of sedimentary rocks, which strike from S.S.W. to N.N.E. The succession is divisible into an eastern and a western portion ; the former being a series of grey and green slates with bands of arenaceous slate (grauwacke), all steeply inclined to the W.N.W., but probably repeated in isoclinal plications, so that their thickness cannot be easily estimated ; five separate groups can, however, be distinguished, and these are not likely to be less than 6000 feet thick. The western group consists of purple grits and conglomerates, with a band of purple slates in the middle, the latter probably lying in the axis of a large and synclinal trough, in which case the real thickness of this series would be only half the apparent thickness, but would still amount to about 6600 feet. This sedimentary series is often called the *Longmyndian.*

The area is bounded on both sides by faults, but outside these are small tracts or portions of a volcanic series, to which the name of *Uriconian* has been given. The chief exposures are on the Wrekin and the Caradoc Hills on the eastern side, and in Pontesford Hill on the western. The group underlies the local Cambrian rocks, and consists largely of rhyolitic lavas, with some agglomerate and bands of gritty tuff and conglomerate. The pebbles in a conglomerate near the Wrekin prove that the rocks of which the surrounding country at that time chiefly consisted were : (1) coarse granitoid gneiss like that of the Wrekin ; (2) crystalline schists, both quartzose and micaceous, of Mesarchæan type ; (3) grits which have clearly been detrital sediments, and still retain a distinct clastic structure.

The relations of these three series to one another is a matter of dispute. The Uriconian lavas seem to be older than the western conglomerates, which are in some places full of pebbles of rhyolite. They are probably newer than the eastern slates, and thus they may be of intermediate date, because there are some indications of an unconformity between the eastern series and the lowest bed of the western series.

Professor Lapworth has suggested a hypothetical explanation of the facts, which on the whole affords the most satisfactory correlation of the Longmynd and Caradoc successions ; this is that the western conglomerates and grits may be really contemporaneous with the volcanic series—that they may, in fact, be the offshore detritus of the volcanic hills (or islands), for the erosion of such volcanoes would go on *pari passu* with the eruption of lavas and ashes, and the detritus derived from them would be spread out on the floor of the adjoining sea.

On this hypothesis the slates and shales of the eastern Longmynd are the oldest rocks in the district, except, of course, the gneisses of the Wrekin, and the general succession would thus be comparable with that of Brittany.

3. In Carnarvonshire there are two tracts where rocks like those of the Uriconian come to the surface and occupy a similar position below the base of the Cambrian system. They are provisionally known by the name of the *Bangor Series*, and seem to be between 3000 and 4000 feet thick, but their base is nowhere exposed and the lowest visible rock in both districts is a massive quartz felsite, which Professor Bonney has shown to have been originally a rhyolitic lava-flow, or set of successive flows.

Writing in 1879, Professor Bonney remarks[1] that "further examination will probably discover more agglomerates and perhaps further subdivide the lava-flows, which certainly seem at present of exceptional thickness and extent. The larger *massif* is about 13 miles long and two at greatest breadth."

4. Pembrokeshire.—Another important tract of Eparchæan rocks is found near St. David's in Pembrokeshire. These were claimed as of pre-Cambrian age by Dr. Hicks in 1876, and were named by him the Pebidian series. They occupy an area of about 7 miles in length with a maximum width of 2 miles (see map, Fig. 2). They have been the subject of much controversy, but the difficulties have gradually been dispelled by successive observers, and Mr. J. F. N. Green's recent mapping of the ground seems to have finally established their relative position and age.

According to Mr. Green's observations, the series consists almost entirely of felsitic and trachytic tuffs, more basic in the lower part, more felspathic and siliceous in the higher part, the total thickness being over 3000 feet. A well-marked band of conglomerate occurs in the middle of the series, and lenticles of shale are seen at several horizons. There do not seem to be any interbedded contemporaneous lava-flows, but rounded pebbles of rhyolite, trachyte, and andesite occur in the tuffs.

It seems therefore that the Pebidian series is entirely fragmental, and that the volcanic material of which it is composed has been spread out under water in the neighbourhood of a large volcano or group of volcanoes. Mr. Green indeed is inclined to believe that, though some of the materials may have been blown out from volcanoes, so as to fall where they are now found, the bulk of them has been washed down from the erosion of a land-surface. The

[1] *Quart. Journ. Geol. Soc.* vol. xxxv. p. 319 (1879).

accumulation of the Pebidian deposits may thus mark a period of temporary quiescence, but if so it was certainly followed by another outbreak of volcanic activity, for the series above described is invaded by a large intrusive mass of granite and by a number of quartz porphyry dykes, which probably proceed from the deeper parts of the granitic mass. That these intrusive rocks are also of pre-Cambrian age is proved by an inland section, where they are cut off and overlain by the Cambrian conglomerate.

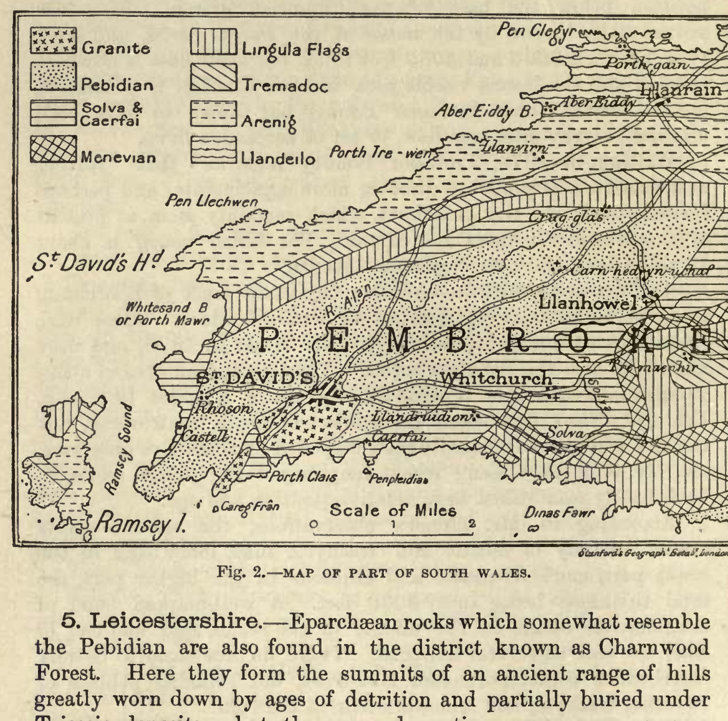


Fig. 2.—MAP OF PART OF SOUTH WALES.

5. Leicestershire.—Eparchæan rocks which somewhat resemble the Pebidian are also found in the district known as Charnwood Forest. Here they form the summits of an ancient range of hills greatly worn down by ages of detrition and partially buried under Triassic deposits; but the exposed portions occur over an area which is about 8 miles long by 5 in its greatest width.

This Charnwood or *Charnian* series has the structure of a broad anticline, which is broken by faults and minor flexures. The apparent thickness of beds exposed, as estimated from Professor Watts' section,[1] is about 3500 feet, but neither base nor summit is seen. The lowest beds are greenish sandy slates, which seem

[1] See *Proc. Geol. Assoc.* vol. xvii. p. 373 (1902).

originally to have consisted largely of pumiceous dust ejected from some volcano or volcanoes ; and they include beds containing visible quartz grains which may have been derived from the detrition of a trachytic lava. The succeeding (Maplewell) groups consist of coarse volcanic breccias, with grits, tuffs, and ashes ; some of the latter being of such fine grain that they now form horn stones and slates generally of apple-green or purple colour.

The highest group has a conglomerate at the base, which contains rounded pebbles of felsitic lava, slate, quartz, and quartzite. This passes up into a hard red sandstone or quartzite, which is of some thickness and includes a band of sandy shales, on the surfaces of which there are what appear to be traces of worm-castings. In the N.W. corner of the area there are some masses of a porphyroid rock and of coarse volcanic agglomerate, which seem to indicate the proximity of a volcanic vent.

From these facts we may infer that there was first a period of quiet sedimentary deposition in the neighbourhood of active volcanoes ; then an epoch of intense volcanic activity during which the bulk of the rocks were accumulated ; afterwards came a pause and a time when the volcanic cones were eroded by the action of rain and streams, with the consequent formation of deposits in a large lake or on the floor of an encroaching sea. Finally, disturbances again took place, and igneous rocks were intruded into the deposits which had thus been accumulated ; these intrusions are chiefly found in the southern parts of the area, and consist of augite-syenite.

6. Smaller Tracts.—About 14 miles S.W. of the Charnwood area, and near Nuneaton in Warwickshire, is a narrow tract of similar volcanic material, which is probably a continuation of the Charnian series, and is here directly overlain by rocks with Cambrian fossils, so that its Archæan age is proved. Another small exposure occurs at Barnt Green, near Bromsgrove in Worcestershire, and there is also a narrow tract of rhyolites and other volcanic rocks on the Malvern Hills, lying on one flank of the Protarchæan gneiss. In Shropshire also small exposures of the Longmyndian and Uriconian rocks come to the surface again in Haughmond Hill and near Lilleshall, from beneath the newer strata which overlie and surround them.

From the occurrence of so many surface exposures of Eparchæan rocks, over an area extending from the western borders of Wales to Charnwood Forest in Leicestershire, we may reasonably infer that the whole of Wales and Central England is underlain by these rocks, except where the still older Protarchæan protrudes through them. The surface formed by the Archæan rocks as a whole is doubtless the floor on which the Cambrian and all succeeding strata rest, and if borings were carried deep enough in any part of England, they would sooner or later reach one of these most ancient rock-systems, or some of the igneous rocks which were subsequently forced up through them.

One such discovery has already been made by a boring at Orton in Northamptonshire, 25 miles S.E. of the Charnwood area, where a quartz felsite (probably a devitrified rhyolite) was found below Rhætic shales and sandstones at a depth of 715 feet.

7. Scotland.—The area of the unaltered Eparchæan series in the N.W. of Scotland is shown in Fig. 1. In that district it is essentially an arenaceous formation, and is known as the Torridon sandstone, or *Torridonian.* But although it is only in that area that the formation can safely be distinguished and coloured, there is little doubt that it enters largely into the construction of the

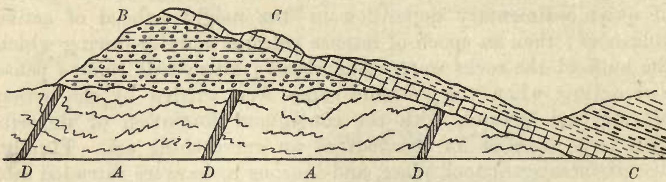


Fig. 3.—DIAGRAM OF THE SUCCESSION IN THE N.W. OF SCOTLAND.

A. Lewisian gneiss.
B. Torridon sandstone.
C. Lower Cambrian series.
D. Dykes in the gneiss.

Moine schists, and consequently that it originally extended over the large area now occupied by those schists, *i.e.* over the whole of Sutherland, Ross, Cromarty, Inverness, Nairn, and the north part of Argyle.

The position of the Torridon sandstones between the Lewisian gneiss and the Cambrian, and at the same time in unconformable relation to both, is so clear in Sutherland and Ross that it has been a recognised fact ever since it was first demonstrated by Nicol in 1856 and accepted by Murchison in 1857, although the true age of the overlying rock, and consequently of the Torridonian, was not ascertained till 1891. The two great unconformities are clearly shown in Figs. 3 and 4.

The unconformity at the base of the Torridonian undoubtedly represents a long lapse of time, during which the great mass of underlying Lewisian gneiss constituted a land-surface, and was carved into bold physical features, comprising lofty hills separated by deep valleys and bordered by undulating plains or plateaus.

From Cape Wrath as far south as Gairloch the surface seems to have been a shelving plateau, eminences of which were not great and were of more or less uniform height ; but south and east of Gairloch the topography was much more varied, the partial removal of the Torridonian sediments revealing a series of buried hills and ridges divided by valleys which in some cases descend to more than 2000 feet below the summits.

"A conspicuous example of the irregularity of the ancient land-surface is found on the flanks of Slioch, which rises above the northern shore of Loch Maree. This great mountain can be shown to partially envelop three distinct hills and to fill up two valleys of pre-Torridonian age. Over 2000 feet of Meall Each, the most easterly of these elevations, are still visible, and the disposition of the surrounding strata shows that it may well have reached 3000 feet. The original sides of this hill were very steep, for their scree-slopes, now compacted into Torridonian breccia, are still distinctly visible. Meall Riabhach, the central hill, forms a conspicuous feature as seen from the further side of the loch, owing to the contrast of the light-grey gneiss of which it consists with the dark-purple sandstones that abut against its sides."[1] The manner in which the Torridon sandstone of Slioch rests against the Lewisian gneiss of Meall Each is shown in

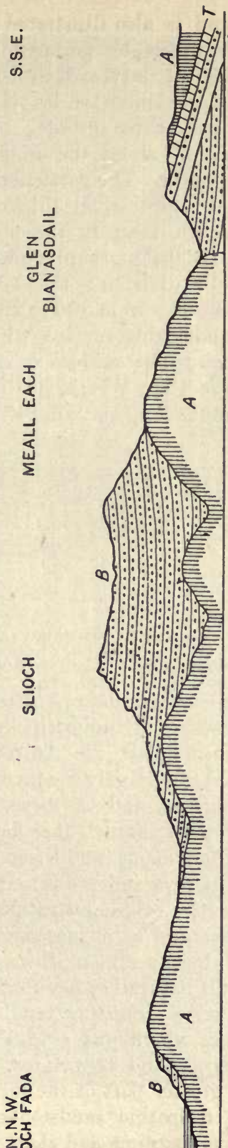


Fig. 4.—Section from Loch Fada through Slioch and Glen Bianasdail.
(Total distance about 4¾ miles.)

A. Lewisian gneiss. *B.* Torridon sandstone. *C.* Cambrian. *T.* Thrust-plane.

[1] Quoted from the *Geol. Survey Memoir* on the "Structure of the N.W. Highlands of Scotland," 1907, p. 277.

Fig. 4, and is also illustrated by the photographic view in Fig. 5, which is taken by permission from a photograph belonging to the Geological Survey of Scotland.

The Torridonian series is of great thickness and has been divided into three groups, but these are by no means equally developed all along the range or strike of the formation from north to south. The particulars given in the Memoir above quoted show that the original thickness of the whole was much greater in the south than in the north. Near Cape Wrath the lower division (Diabaig group) appears to be absent, as well as part of the middle division; the lower comes in farther south and its thickness varies from 500 to 2500 feet, according to the irregularities of the underlying surface, while in Skye it has increased to over 7000 feet. The middle or Applecross group is only 1100 feet thick near Cape Wrath, but in Ross it reaches a maximum thickness of 8000 feet, and in Skye there is 5000 feet of it without a

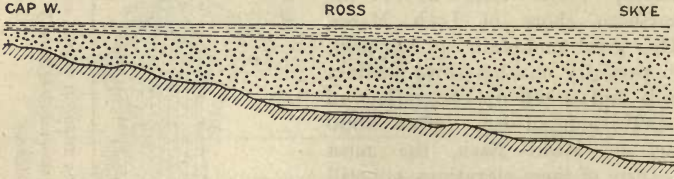


Fig. 6.—DIAGRAM OF THE ORIGINAL SUCCESSION OF TORRIDONIAN DEPOSITS.

3. Aultbea group. 2. Applecross group. 1. Diabaig group.

summit. The highest Aultbea group has suffered from erosion, but reaches a maximum thickness of 3000 feet in Ross.

Assuming that the Aultbea group was originally continuous, but has been largely removed by post-Torridonian erosion, both in Sutherland and in Skye, it seems probable that the average original thickness of the formation varied by increasing southwards from about 2000 feet in the Cape Wrath district to about 10,000 in Ross and possibly 16,000 in Skye.

Thus the original stratigraphy of the Torridonian series may be represented as a succession of overlapping beds, the lowest and oldest lying to the southward (see Diagram, Fig. 6). From this we should naturally infer that the Torridonian is a series of deposits formed on a subsiding land surface, or beneath the waters of a large lake which was gradually increasing in size, and extending over a larger and larger area.

The greater part of the formation consists of more or less coarse grained felspathic sandstones, with some thin intercalations of micaceous flagstone and shale; both the upper and lower divisions, Slioch. Meall Each.

T

G

Photo *H.M. Geol. Survey.*

Fig. 5.—VIEW OF THE TORRIDON SANDSTONE OF SLIOCH (T), RESTING ON THE LEWISIAN GNEISS (G) OF MEALL EACH, NEAR LOCH MAREE, ROSS-SHIRE.

however, include a considerable thickness of dark-grey sandy shales. Mr. Hinxman remarks that "the rain-pitted and sun-cracked surfaces of the shales and mudstones seen on Loch Torridon and elsewhere show that the fine sediments of the lowest group are shore deposits and cannot be regarded as due to deeper water conditions."

The basement beds of the Torridonian generally form a coarse conglomerate or breccia, the components of which have been chiefly derived from the Lewisian gneiss. This conglomerate is not confined to one stratigraphical horizon, but forms a continuous border to the formation, covering the inequalities of underlying surface, and often climbing up the slopes of the buried hills for two or three thousand feet above the actual local base of the series. But except in this basal conglomerate fragments of the Lewisian gneisses are by no means abundant, and the bulk of the pebbles found in the coarser sandstones consist of rocks which differ from any now exposed in Sutherland or Ross. They include various kinds of sedimentary, metamorphic, and igneous rocks, *i.e.* vein quartz, quartzite, chert, jasper, grits, felsite, and felspar-porphyry. They have been examined by Dr. Teall, from whose description in the Memoir above quoted it appears that the quartzites, cherts, and grits are much altered and silicified sedimentary rocks, while the felsites and porphyries are "identical in all essential respects with the felsites [*i.e.* devitrified rhyolites] belonging to the Uriconian series of Shropshire."

From these curious facts we may certainly infer the previous existence of an important volcanic and sedimentary series. The sedimentary series may have been a portion of the Mesarchæan system of the Central Highlands, but there seems also to have been a volcanic group comparable to the Uriconian and Bangor series of Southern Britain. This vanished formation must have overlain the Lewisian gneiss and must have been the principal source from which the component materials of the Torridonian deposits were derived. We are thus enabled to form some idea of the immense amount of rock-material which had been broken up and removed by detritive agencies before the surface of the Archæan land was reduced to the form it presented when buried beneath the Torridonian conglomerates. We see that not only has a formation, which must have been several thousand feet thick, been completely destroyed, but that the same agencies continued their work of erosion till the older Archæan gneisses were themselves trenched by valleys which are over 2000 feet deep.

The depth and extent of the denudation thus revealed to us creates the impression that the break between the Archæan and the

Torridonian systems represents an enormous period of time, but this is a point to which further reference will be made in the sequel. Here it is sufficient to remark that the Torridonian series must have been formed during quite a late portion of Eparchæan time.

B. *Physical History and Geography*

From the brief account of the Eparchæan rocks given in the preceding pages it will be apparent that it is not easy to form a correct idea of the relative ages of the rock-groups which occur in the several more or less distant localities, and that in one case (Shropshire) even the local succession has not yet been thoroughly established. It is of course impossible to read the history of any period until the succession of the deposits has been ascertained, and at present all that can be done is to build up an inferential or theoretical succession on the most probable basis, and to indicate the probable history of events in the order thus suggested. For this purpose I have relied upon the following facts :—

1. That in Central Brittany we seem to have a nearly complete sedimentary development of the system ; the oldest portion consisting of fine sediments only, while the higher part includes conglomerates and flagstones.

2. That in Northern Brittany a part of the series is replaced by volcanic rocks.

3. That the French succession strengthens the view that the rocks of the eastern Longmynd are older than those of the western, and may be older than the Uriconian series.

4. That the Torridonian of Scotland is to a large extent later and newer than any other of the British groups, except perhaps that of the western Longmynd.

From the succession in Brittany we gather that in the earlier part of the period the whole of that region was covered by the waters of a sea or ocean. This *Brioverian* sea may have extended northward through Northern Brittany and Normandy to Southern and Western England as far as the Longmynd in Shropshire.

The slates of the eastern Longmynd exhibit certain phenomena from which several important inferences may be drawn ; these are the prints of raindrops and sinuous tracks of worms which occur on the surfaces of some of the beds. These marks testify to several facts : they show which are the upper surfaces of the beds, for a raindrop produces a cup-shaped depression ; they prove that there were times when the water receded so as to leave a surface of mud which was capable of receiving and retaining these impressions.

Now the preservations of rain-prints is only possible under one or two geographical conditions: (1) that of a flat, muddy sea-shore from which the tide retreats to a great distance, and where there is a wide space between the level of high spring tides and high neaps; or (2) that of a large lake which is subject to seasonal variations of water-level, so that in a dry season a broad portion of its floor is exposed and dried by the sun before it is again covered by the returning waters.

It is very probable that, at this early period of the earth's history, when the moon must have been much nearer than it is now, the daily rise and fall of the tides was greater than it is at the present time, and also that the difference in the vertical height of spring and neap tides was greater. Under such conditions there would be many shallow bays where mud-flats would be exposed to the air and the sun for the greater part of a fortnight, so that the mud would become sufficiently dried and hardened to retain the prints on its surface when the next spring tide crept quietly over it and laid down its load of mud or silt on the top of it. Consequently we may take these rain-prints as evidences not only of tidal action, but also of a great general rise and fall of the tides. This matter will be mentioned again in the sequel.

Whether this early sea was salt or comparatively fresh and by what kinds of creatures it was tenanted, are interesting subjects of speculation, on which, however, we cannot here dwell at any length. With respect to its salinity it must suffice to say that there are good reasons for believing that modern ocean-water is salt, because the proportion of sodium chloride in it has been gradually growing larger throughout the whole duration of geologic time; also that the water of the first cool habitable ocean must have more nearly resembled the average river-water of the present day, and must have held in solution larger quantities of lime and magnesia and much less sodium than is now found in sea-water.

As regards life in Eparchæan seas we know little merely because few organic remains have yet been discovered. This may, of course, be due to an original scarcity of life and its limitation to forms of low and primitive types, but in view of the many and varied forms of animal life which are known to have existed in the succeeding Cambrian period, it is much more likely that many kinds of animals did exist, but that they did not possess any such hard parts as would remain after death to testify to their existence; in other words, that they were mostly soft-bodied creatures without hard shells, tests, or skeletons, or with coverings of such a thin and easily soluble nature that they soon fell to pieces on the sea-floor.

In some parts of the British region volcanoes may have been in active operation throughout nearly the whole of the period ; it is certain at any rate that the greater part of Wales and of Central England was for a long time occupied by groups of volcanic vents, from which copious flows of lava were poured out, and enormous quantities of volcanic dust and lapilli were ejected and spread out in every direction. Part of the area occupied by the deposits which have been called Pebidian, Uriconian, and Charnian may have been a land-surface on which volcanic cones were formed, but other parts seem to have been shallow seas or bays. There is no evidence which favours the idea of deposition in lakes rather than in seas communicating with one another in a manner similar to that of the seas and oceans of the present day.

The absence of lava-flows in the Pebidian series, and Mr. Green's inference that the deposits represent the destruction of a volcanic area rather than the contemporaneous ejections from a volcano, have been mentioned on p. 33 ; but it seems quite possible that the volcanic activity of this period may have been on a very large scale, and the eruptions both frequent and highly explosive in character, so that the ejected materials were not only large in quantity, but were distributed to considerable distances from some of the largest volcanoes.

In this connection it should be remembered that near Bangor, in Carnarvon, about 90 miles to the northward, there is a tract of contemporaneous rocks which seem to be mainly if not entirely a terrestrial volcanic series. They commence with a massive rhyolitic lava-flow, and in Professor Bonney's opinion the materials of the overlying fragmental series have been derived partly from the subaerial erosion of these lavas, and partly from ashes and lapilli ejected by sporadic volcanoes which formed a later phase of the volcanic activity. "Whether volcanic action continued during the time when the conglomerates of Fair-ffynnon, etc. were formed is uncertain. The lapilli in them are in some cases not water-worn, but then they may have been derived from the destruction of cones of scoria, which no doubt rose among and even upon the neighbouring lava-flows. . . . The uppermost beds at Bangor certainly seem to indicate volcanic action, but the ejecta are very different, and the outbursts were probably very local."

Again the Uriconian lavas of Shropshire and those of the Malverns indicate the existence of active volcanoes erupting flows of rhyolitic lava. The fragmental rocks associated with these lava-flows exhibit no signs of having been deposited under water, but are such as might well have been accumulated on a land-surface formed of the Protarchæan gneisses with which they are in contact. We may therefore imagine that these volcanoes broke out on a ridge formed of the ancient crystalline rocks, though this ridge may have been an island or part of the coast-line of a peninsula, for at Lilleshall, about 6 miles north of the Wrekin, the Uriconian felsites and breccias are associated with slates which resemble those of the Charnwood area.

In the latter district the general conditions seem to have been similar, for as Messrs. Hill and Bonney wrote in 1878: "The rarity of conglomerates, grits, and rounded detrital materials seems to indicate the absence of either rivers or tidal currents. Such a district, then, as the Phlegræan Fields, consisting of many low lakes or lagoons (*i.e.* near a sea-coast), would seem to supply the conditions required for the formation of these Charnwood rocks. The lowness of the hills and the porosity of their materials would be unfavourable to rivers; the ash would settle down in quiet waters, little rolled, or be spread out upon the plain. The land, owing to the frequent showers of ash, might be unfavourable to vegetation, and the volcanic disturbances might render the waters unprolific." [1]

At the time the above was written the authors were under the impression that there were no truly igneous rocks in the Charnwood series, but they corrected this mistake in a later paper (1891), and now believe that some lava-flows do occur in that series, though the rock is of a peculiar character. It is, in fact, a crushed quartz porphyry, and, to express this condition more briefly, the term "porphyroid" has been used by some authors. Professor Bonney has kindly informed me that he still thinks the Charnwood volcanoes were local and not very large, that they were almost restricted to the northern and western part of the area, and that the surface was mainly a terrestrial one. He is also inclined to believe that the predominance of the fragmental deposits indicates, as I have suggested in the case of the Pebidian, that the eruptions were of a highly explosive nature, so that actual lava-flows were few and small.

Lastly we have to consider the conditions under which the Torridonian series was formed. The clear evidence of the existence of a previously-formed volcanic series, which was undergoing erosion and destruction to provide the materials of the Torridonian, has already been mentioned; and it was stated that the fact seemed to indicate processes of detrition and deposition which must have occupied an immense period of time.

We must remember, however, that the operation of detritive agencies may have been much more rapid at this early epoch of the earth's history than it is at the present day, and consequently that the time occupied by such processes may have been much less

[1] *Quart. Journ. Geol. Soc.* vol. xxxiv. p. 211.

than would seem necessary if the work of detrition and denudation was gauged by modern standards.

In this connection the freshness of the felspar grains in the Torridonian sandstones has some significance. It was remarked by Professor Bonney, as long ago as 1886, that the finer beds are sometimes almost exclusively composed of quartz and felspar, and "that the felspar appears to have been broken off from the parent rock while still undecomposed," so that the disintegration and breaking-up of this rock must have been accomplished without material decomposition of the felspar. He did not, however, venture to speculate on the cause of this peculiarity.

This freshness of the felspars, which is not confined to the Torridonian, but is the prevalent condition in both Eparchæan and Cambrian rocks, may perhaps be explained in the following way. It is probable that the land of Eparchæan time was for the most part bare and barren; some soil may have been accumulated on the lower levels, but we do not know whether even the most lowly plants were yet in existence, and the higher levels were probably entirely devoid of vegetation and of soil. If this was so there would be no carbonic acid nor any kind of humic acid for the rain falling on the surface to take up in solution, and consequently the rain-water could not exercise much chemical effect and would not decompose the felspars.

Professor Bonney has also reminded me that the climate may have been rather more of the desert type in this region, with a considerable daily range of temperature, a condition of things which is always very favourable to the splitting and splintering of rock surfaces without decay or decomposition.

The explanation above suggested to account for the condition of the felspars will at the same time account for the rapid accumulation of great thicknesses of rock-material, such as the 15,000 feet of Torridonian deposits in Skye; for the bareness of the rock-surfaces would expose them to the full effects of the sun's heat by day, and the consequent contraction by night, as well as to the mechanical erosion of running water during the rainy season. Thus it is highly probable that in these early days the processes concerned in the disintegration of rock, the removal of detritus and its deposition in lake or sea were carried on more rapidly than those of the present day.

On the other hand, we must beware of going to the other extreme and imagining that the difference in the rate of erosion, and consequently of accumulation, was very great. Other facts indicate that most of the natural processes concerned in the work were similar to those of the present day. As Sir A. Geikie has remarked : "The enclosed pebbles are not mere angular blocks and chips, swept by a sudden flood or destructive tide from off the surface of the land, and huddled together in confused heaps over the floor of the sea. They have been rounded and polished by the quiet operation of running water, as stones are rounded and polished now in the channels of brooks or on the shores of lake and sea." [1]

The rain-prints and sun-cracks which have been observed on some of the Torridonian beds [2] show that there were times during which the water retreated from the shores and left large spaces exposed to the action of sun and rain. It has been supposed that the Torridonian strata were accumulated in a large lake or inland sea, and that these markings were evidence of its occasional shrinkage ; but Lyell long ago showed that such marks could be formed on the shores of a tidal sea, and his description of the manner in which rain-marks and sun-cracks are both formed and preserved on the mud-flats which border the Bay of Fundy on the coast of Nova Scotia is well worth quoting. Slightly abbreviated, it is as follows :—

"A peculiar combination of circumstances renders these mud-flats admirably fitted to receive and retain any markings which may happen to be made on their surface. The sediment with which the waters are charged is extremely fine . . . and as the tides rise 50 feet and upwards, large areas are laid dry for nearly a fortnight between the spring and neap tides. In this interval the mud is baked in summer by a hot sun, so that it solidifies and becomes traversed by cracks caused by shrinkage. Portions of the hardened mud may then be taken up and removed without injury ; and a cross section of it exhibits numerous layers formed by successive tides. . . . When a shower of rain falls, the highest portion of the mud-covered flat is usually too hard to receive any impressions; while that recently uncovered by the tide near the water's edge is too soft. Between these areas a zone occurs, almost as smooth and even as a looking-glass, on which every drop forms a cavity of circular or oval form, and if the shower be transient, these pits retain their shape permanently, being dried by the sun and being then too firm to be effaced by the action of the succeeding tide, which deposits upon them a new layer of mud." [3]

The ripple-marked surfaces which are very common on some of the shales, flagstones, and finer sandstones indicate the existence

[1] See "Address to Section C of the Brit. Assoc." (1899), and *Geol. Mag.* for 1899, p. 462.

[2] See "Geol. Structure of N.W. Highlands," *Geol. Surv. Mem.*, 1907, pp. 273, 325, and 359.

[3] Lyell's *Principles of Geology*, 10th Edition, vol. i. p. 333.

of steady currents and of winds producing wave oscillations under conditions that can be matched at the present day.

Lastly, the stratigraphy of the Torridonian series, as represented theoretically in Fig. 6, indicates not only the rapid and continuous destruction of a northern land-surface, but points to the gradual invasion of this land by waters which lay to the south of it. This Torridonian sea may have been continuous with the Brioverian and Longmyndian sea : at first, perhaps, it formed a large lake or land-locked bay, resembling the Bay of Fundy, but as time went on and the subsidence progressed, the superficial extent of the water would be gradually increased until, as seems very likely, the whole of the Scottish region was submerged. Thus the Torridonian is the record of a great subsidence by which a northern land was buried under a pile of its own detritus.

CHAPTER III

THE CAMBRIAN PERIOD

A. *Stratigraphical Evidence*

Cambrian rocks rise to the surface in several parts of the British Islands, but they nowhere occupy any very large tract of country, so that we can only compare their isolated exposures, and cannot trace their stratigraphical variations from one district to another. In England and Wales there are five districts where rocks referable to the Cambrian system occur—South Wales, North Wales, Shropshire, Warwickshire, and the Malvern Hills. They occur again in Ireland and in the far north of Scotland.

1. England and Wales.—Wherever the base of the system is exposed, the basement bed is found to be a conglomerate containing fragments of Archæan rocks, and resting unconformably on a very uneven surface of those rocks; the conglomerate being probably in process of formation at different levels throughout the whole of the period, and belonging, therefore, to different stages at different places.

The Cambrian system attains its greatest thickness in North Wales, where it is estimated to be about 11,000 feet thick; but the most complete succession, so far as palæontological divisions are concerned, is found in South Wales. The following are the groups recognised:—

Tremadoc Slates Lingula Flags	Upper Cambrian.
Menevian Beds Solva Group	Middle Cambrian.
Caerfai Group	Lower Cambrian.

In Pembrokeshire (see map, Fig. 2) the Caerfai group consists chiefly of sandstones and grits, with a conglomerate at the base. It is about 1800 feet thick, and is characterised by the presence of the Trilobite *Olenellus.* The Solva group consists of grits and slates, and the Menevian of flagstones and slaty shales. They are together about 2400 feet thick, and are characterised by the occurrence of *Paradoxides*. The Lingula flags are here about 2000 feet thick, and consist largely of flags and sandstones, which have ripple-marked surfaces, and indicate rather shallow water. *Olenus* is the prevailing Trilobite. The Tremadoc Beds are flags and slates with a thickness of about 1000 feet.

In North Wales the Solva and Caerfai groups have not yet been separated from one another, but are together known as the Harlech Beds (see map, Fig. 7). In Merioneth these are generally supposed to be more than 6000 feet thick, and the latest estimate gives them a thickness of about that amount.[1]

To the north-west they plunge beneath the great Snowdon syncline, and when they reappear in Carnarvon they present a similar series of slates and grits (the Llanberis slates), but, as far as the thickness can be estimated in such a faulted region, there is not more than 3000 feet of such sediment before reaching the basal conglomerate. This is exposed along the eastern side of the main Archæan ridge by Llyn Padarn, etc., and again on the western side, where it is succeeded by some thickness of grits, till they are faulted against Ordovician shales.

In the extreme west, near Carnarvon, the basal conglomerate is overlain by grits and sandstones, which have been referred to the Harlech Beds, but as only a small thickness of Lingula flags succeed before the Arenig shales (Ordovician) are reached, it is quite possible that all the Cambrian beds here are of Lingula flag and Tremadoc age; the Harlech group having thinned out, and allowed the Upper Cambrian to rest directly on the Archæan. In the absence of fossil evidence this is a more likely view, as the basal and littoral deposits would have a coarse conglomerate character whether they were of older or younger Cambrian age.

If, therefore, we regard the western Cambrians as Lingula flags, it follows that the whole of the Harlech series has thinned out in the space of 4 miles. The probability of this is increased by the fact that the Lingula flags themselves give evidence of a westerly attenuation; in Merioneth they and the Tremadoc have a thickness of 7000 feet, but near Llanberis they are supposed to be less than 3000 feet. On the west side of the Dinorwig ridge the whole of the Cambrian is not more than 1000 feet, so that it may reasonably be regarded as representing the Upper Cambrian. These beds are traceable northwards to Maes y Gaer, near Aber, but west of this, near Bangor, there is only a conglomerate and some sandstones between the Arenig shales and the Archæan rock.

[1] Lapworth and Wilson in *Geological Magazine*, 1910, p. 161.

The evidence of a north-westerly overlap is thus very strong, and it would appear that about 10,000 feet of rock have thinned

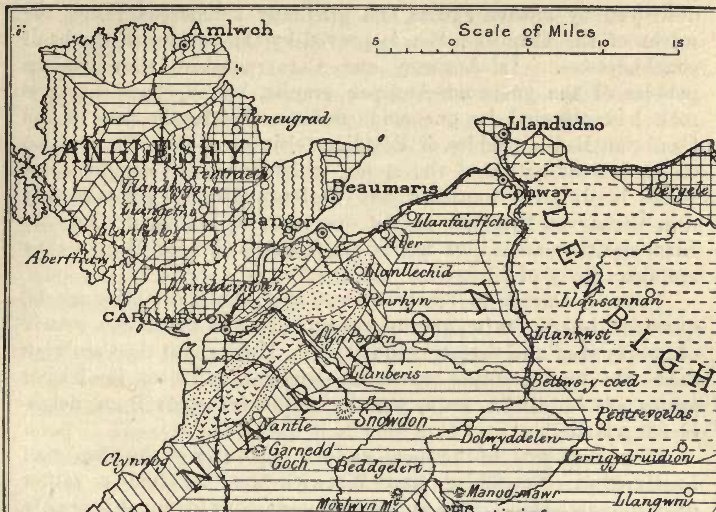


Fig. 7.—GEOLOGICAL MAP OF A PART OF NORTH WALES

out and disappeared between Harlech and Bangor. These facts point to the existence of land to the west of Wales, and the conclusion is confirmed by the fact that the oldest Cambrian rock found in Anglesey is a sandstone with Tremadoc fossils having a basal conglomerate which rests on the Archæan rocks.

That land composed of Archæan rocks was being rapidly destroyed by erosive agents, and gradually submerged below the waves of the Cambrian Sea, is proved by the pebbles in the basal conglomerates. In Anglesey and Carnarvonshire they contain pebbles of the gneissoid Archæan granite, which show that this rock had assumed its gneissoid condition before the date of the Cambrian Beds ; pebbles of Pebidian felsites and porcellanites also occur, but the nature of the stones which form the conglomerate varies in different localities, and Professor Hughes remarks that near Carnarvon they are chiefly quartz, near Llanddeiniolen and Llanberis they are all, or nearly all, felsite, and near Bangor they are also chiefly of felsite.

Near St. David's in Pembrokeshire the pebbles comprise quartz, quartzite, quartz-felsite, granite, porcellanite, and schist in a matrix of quartz sand and decomposed felspar. Throughout the Cambrian series the sand is often coarse and angular, and even the felspar grains are but little worn, showing rapid transport from neighbouring land.

If we now pass to the more eastern exposures of the Cambrian in Hereford, Shropshire, and Warwickshire, we find a rather different succession. The amount of arenaceous sediment is greatly diminished, and is entirely confined to the lower part of the series, while the total thickness is very much smaller.

The gneissic rocks of the Malvern Hills are flanked on the west by a conglomerate which passes up into greenish sandstones between 500 and 600 feet thick (Hollybush sandstones), which appear to be the sole representative of the Harlech Beds of Wales. Above these come 1000 feet of black and grey shales, with Lingula flag and Tremadoc fossils.

A similar succession is found in Shropshire, where the local Archæan rocks are unconformably overlain by a pebbly quartzite passing up into the greenish (Comley) sandstone, which is succeeded by the Shineton shales ; the fossils of the sandstone proving it to represent both the Caerfai and Solva groups, while the shales are the equivalents of the Lingula flags and the Tremadoc slates. The basal conglomerate contains pebbles of the Uriconian lavas, and the green colour of the sandstones is due to the superabundance of chlorite and other minerals derived from the ferromagnesian constituents of volcanic rocks.

From the Caradoc district the Cambrian rocks plunge eastward between the Ordovician and Silurian deposits, but rise to the surface again in Worcestershire (the Lickey) and in Warwickshire, near Nuneaton. In the latter locality we find a somewhat different development indicative of still greater distance from the mainland, though apparently deriving much material from the destruction of islands consisting of the Caldecote and Charnwood rocks.

The lowest division is still arenaceous, and its basement bed is a quartzite conglomerate, sometimes containing large boulders of the Caldecote rocks; the overlying quartzites are interbedded with layers of purple and grey shale, and the highest beds contain glauconite, so that they were originally glauconitic sands; moreover, they are associated with red sandy shales and a bed of red limestone full of Pteropod shells (*Hyolithes* and *Orthotheca*). These deposits indicate slow accumulation in shallow but fairly clear waters, far from the embouchure of any large river, probably near islands and within the influence of strong currents. Their total thickness is about 600 feet.

The succeeding (Menevian) group consists of purple sandstones and shales (600 feet), above which is another set of shales representing the Lingula flag and Tremadoc groups, but only 1000 feet thick. They seem to indicate the slow deposition of fine mud at some distance from land and in deeper water, after all the volcanic islands had been planed down and submerged.

In the east of England, Suffolk, Essex, Herts, and Middlesex, many deep borings have been made through the Cretaceous rocks, and have proved that a subterranean platform of Palæozoic rocks underlies the whole of the London basin, and extends northward, at least as far as Culford, near Bury St. Edmunds. Some of these borings have proved that Silurian and Devonian Beds enter into the structure of this buried land, while at Harwich, Weeley, Stutton and Culford slaty rocks of uncertain age were found.

At Harwich and Weeley the rocks are hard greyish-black or dark purplish-grey slates or argillites; at Stutton, on the north side of the Stour, there are greenish-grey banded slaty grits (quartzo-phyllades); and at Culford, in West Suffolk, green and grey slates with bands of dark hornstone or compact argillite rise to within 638 feet of the surface. All these rocks have a family likeness, and are very different from those found by other borings to the southward.

Professor Watts examined some of the samples obtained, and his observations (published in the *Summary of Progress of the Geological Survey* for 1896) went far to prove that the Harwich rock was not of Carboniferous age, as had been imagined, and that the supposed *Posidonia* occurring in it was not an organism of any kind but only a conchoidal fracture.

Samples from these borings have recently been submitted to M.

Mourlon, the Director of the Geological Survey of Belgium, and he informs me that those from Harwich and Weeley much resemble the dark slates of the Revinian division of the Cambrian of Ardennes; and that the sample from below 1500 feet at Stutton compares very closely with the quartzo-phyllades of Villers la Ville (S.W. of Brussels), formerly referred to the Ordovician but now classed by M. Malaise as Upper Cambrian.

In the north of England the oldest rocks exposed are the Skiddaw slates of the Lake District, which are believed to include representatives of the Tremadoc slates and the Lingula flags. Their base is not seen, and it is very probable that they are the upper portion of a thick Cambrian series like that of Wales. Slates of the same age occur in the Isle of Man.

South of the Malvern Hills no Cambrian rocks come to the surface in England, and there is some reason to think that part of the south-west of England was land during the Cambrian period; although both Ordovician and Archæan rocks occur in Cornwall, no Cambrian has yet been recognised in that county. The base of the Ordovician has not yet been ascertained, the conglomerate which was formerly referred to that position having proved to be the base of the Devonian (see p. 103). There are rocks which are apparently older than the fossiliferous Ordovician (Llandeilo), but their age has not been determined because no fossils have been found in them in spite of careful search by the officers of the Geological Survey. Neither has any evidence of unconformity, leading to the supposition that some of them might belong to an older system, been observed in the district.

2. France.—Crossing over to Brittany, we find Cambrian rocks coming in again between the Brioverian (Phyllades de St. Lo) and the base of the Ordovician. In the west and north of Brittany they are poorly developed, and it is only in the south and east that the system is complete. Thus in the north, by Lannion and Tregnier, there is only basal conglomerate surmounted by 300 to 400 feet of red and green slates; near Brest there is a similar succession, and the conglomerates contain a variety of rocks derived from the Protarchæan and Brioverian series. No fossils have been found in the slates, but as they are succeeded conformably by the "Grès Armoricain" (Arenig) it is probable that they represent only the highest part of the Cambrian system (Tremadoc Beds).

In the south and S.E. of Brittany a much thicker series is found. Near Montfort-sur-Meu and Pontréau (W. and S. of Rennes) the basal purple conglomerates are 1700 feet thick, and are overlain by red slates with an estimated thickness of 7000 feet. Still farther east in Mayenne there is a more varied series comprising a basal conglomerate, slates, grits, and limestones, coarse sandstones and porphyritic lavas, and finally green slates and flags containing *Lingula* (*Thomasina*) *Criei.* Although only a few specimens of *Lingulella* and *Dinobolus* have been found in the lower beds, M. Æhlert believes them to represent the Lower and Middle Cambrian series.

In Normandy (Calvados and Orne) there is also some thickness of the Cambrian, the usual basal conglomerate being succeeded by red slates and massive limestones (marble), which are overlain by green slates with bands of limestone. The limestones, however, thin out westward in the Cotentin, where the highest beds are purple and green slates conformably overlain by felspathic sandstones. No fossils have been found, and the total thickness is nowhere more than 600 feet from the base to the top of the slates. Probably all is Upper Cambrian. With regard to the felspathic sandstones, which also occur in the north of Brittany, they have

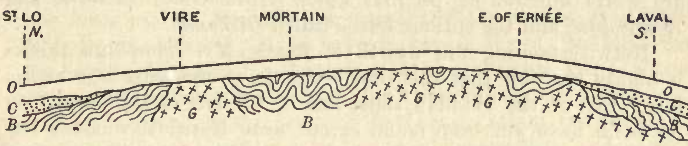


Fig. 8.—DIAGRAMMATIC SECTION FROM ST. LO TO LAVAL, BRITTANY.

(Distance about 70 miles.)

O. Ordovician. *B.* Brioverian.
C. Cambrian. *G.* Granite.

usually been regarded as belonging to the Cambrian, but they pass conformably into the "Grès Armoricain," and Professor Barrois informs me that he now considers them to be a facies of that sandstone, and consequently of Ordovician age.

Having thus briefly indicated those areas where Cambrian deposits are found, we must take note of those parts of the Armorican region where they do not exist, where the Ordovician rests directly on pre-Cambrian rocks. This is notably the case in the long and deep synclinal trough which extends from Lanfains and Uzel on the west by Colinée, St. Jouan, and St. Aubin to Vitré on the east. To the N.E. also by Mayenne, Mortain, and Domfront there is the same absence of Cambrian between the Grès Armoricain and the older rocks, the relations of these three series of rocks being as shown diagrammatically in Fig. 8.

Thus a large area of Eastern Brittany, together with parts of Maine and Orne, seems never to have been covered by the Cambrian sea. During the earlier part of the period the whole of

Western and Northern Brittany also appears to have been land, but at a later epoch the sea evidently invaded these parts of the region and reduced the land-area to the condition of an island. The position of this island is indicated on Fig. 28.

3. Ireland.—Much difference of opinion has existed about the oldest rocks in the south-east of Ireland (Wexford, Wicklow, and Dublin), some regarding them as equivalents of the later Archæan rocks in Anglesey and Shropshire, and others accepting the general view that they are most probably Cambrian. They are often called the Bray series, and consist of grey, green, and purple slates and grits, with thick beds and masses of quartzite.

The uncertainty of their age is due to the scarcity of fossils, for although they are exposed over considerable areas, not a single example of the Welsh Cambrian faunas has yet been found in them, in spite of repeated search by the staff of the Irish Geological Survey. The only organic remains hitherto obtained from them are worm burrows of peculiar kinds (*Histioderma*, *Scolithus*, and *Arenicolites*) and the curious fossils called *Oldhamia*.

Notwithstanding this dearth of fossils, Mr. Lamplugh thinks it highly probable that the Bray series is of the same age as the lower part of the Skiddaw slates and of the Isle of Man, in which no fossils have yet been found except near Keswick, where a few Graptolites suffice to prove that the beds containing them are of Tremadoc age. He also points out that the rocks of the Bray series are very similar to those of the Manx slates.[1]

Professor Grenville Cole informs me that he concurs in this view because it appears to be confirmed by the occurrence of *Oldhamia* in the Upper Cambrian rocks of North America.[2] Its occurrence in the Upper Cambrian of Farnham (Quebec) is confirmed by Mr. Walcott, who also described a new form under the name of *O. occidens* from beds of Upper Cambrian or Lower Ordovician age near Troy in the United States. With regard to this latter Professor Cole has remarked[3] that if it is "to stand as a species, some forms from Bray will have to be included in it, such as one figured by Mr. W. H. Baily in 1865" (*Geol. Mag.* vol. ii. p. 394, Fig. 4 *c*).

Again, the form called *Oldhamia antiqua* has been found in the slates of Fuman in the Ardennes, these beds being succeeded by others containing *Dictyograptus* and referred to the Upper Cambrian.

Oldhamia radiata has also been found at Tubize in Belgium, in rocks which underlie slates containing graptolites of the Arenig fauna.

[1] "The Geology of the Country around Dublin," *Mem. Geol. Survey* (1903).
[2] See C. D. Walcott in *Proc. U.S. Nat. Mus.* vol. xvii. p. 313 (1894).
[3] "On Oldhamia and Histioderma," *Irish Naturalist* for 1901, p. 84.

Lastly, the supposed unconformity between the Ordovician and the Bray series in Ireland seems to be of an illusory character. The beds formerly regarded as conglomerates in Wexford prove on re-examination to be crush breccias, and elsewhere the Bray slates and the lowest Ordovician series are so squeezed and plicated together that it is difficult to find a dividing line, and so far as Messrs. Egan and M'Henry[1] could ascertain, there is no evidence of any stratigraphical break between them.

On the whole, therefore, it seems most probable that the Irish succession is a continuous one, and as the lowest recognisable fauna is of Arenig age, it follows that the Bray series would be of Tremadoc and Upper Cambrian age.

4. Scotland.—No Cambrian rocks have yet been recognised in the north of Ireland, nor in the southern nor the central parts of Scotland. It is very probable, however, that the Skiddaw slates extend northward from Cumberland under the Ordovician and Silurian rocks of the Southern Uplands, and Cambrian rocks may also form part of the schistose complex of the central Highlands. At present, however, it is only in the N.W. of Scotland that the actual existence of a Cambrian series is known, along a tract of country which extends from Loch Eriboll on the north coast to Loch Carron on the coast of Inverness. Here the Cambrian presents a special local facies, but is fairly complete and consists of the following succession of deposits :—

Middle and Upper Cambrian, 1400 feet		Grey limestones with layers of chert.
		Dolomites and limestones, largely made of worm-casts.
		Dark and light grey dolomites with layers of chert nodules.
		Light-coloured dolomites and limestones with bands of chert, but few fossils.
Lower Cambrian	220 feet	Grey dolomites and white limestones, with *Salterella.*
		Dolomitic grits with *Salterella* (= Serpulite grit).
		Dolomitic shales and mudstones with *Olenellus.*
	500 feet	Fine-grained quartzites with worm casts and burrows, *Scolithus* (= Pipe-rock).
		Quartzites and grits with pebble bed at base.

The following remarks are gleaned from the account of these beds given by Messrs. Peach and Horne in the *Geological Survey Memoir* on the North-West Highlands of Scotland.

The character of the surface on which the Cambrian series rests presents a great contrast to that which lies below the Torridonian series ; the latter is a land-surface of deeply sculptured hills and valleys (see p. 37), but the platform on which the Cambrian lies is

[1] See *Sum. Prog. Geol. Survey* for 1898, p. 57.

a nearly uniform plane, which may safely be regarded as a plane of marine denudation. It is clear that in this basal plane and in the overlying set of quietly deposited fossiliferous strata, which differ so greatly from the coarse and lifeless Torridonian sandstones, we have the record of a great subsidence, during which the sea advanced on the land and planed down its inequalities, till a gently sloping surface was produced to become the platform on which the Cambrian sediments were accumulated.

The prolonged chemical action of the sea-water, which may by this time have become appreciably salt, is shown by the fact that where the Cambrian rests on the Hebridean gneiss the latter has been epidotised and the felspars have been altered into a mineral called agalmatolite. Where it covers Torridonian sandstones these are bleached from red to grey and the felspars are kaolinised, so that the beds near the junction contrast strongly in colour and texture with the unaltered rock below.

In the lower quartzite, which has a thickness of 200 feet, pebbles are not rare and false-bedding is frequent, so that Mr. Peach infers that it was accumulated rapidly in comparatively shallow water and under the influence of strong currents. "In the northern part of the region it contains few or no intercalations of shale, but towards the extreme south and south-west, beds of micaceous shale, sometimes 10 feet thick, make their appearance towards the base of the group, showing that the 'mud-line' was occasionally reached in that direction" (*op. cit.* p. 369).

"During the accumulation of the upper quartzite, quieter conditions of deposit seem to have prevailed in slightly deeper water further from the shore." Moreover, the water seems to have been very clear, for the topmost bed of this rock is in some places sprinkled with grains of glauconite. In this quartzite the cylinders of sand commonly known as *pipes* are very abundant; they are the castings of worms, and as they are of different sizes and character in different beds, they seem to indicate the existence of several kinds of Annelids.

The succeeding beds of calcareous shale and mudstone indicate still further subsidence, and possibly greater distance from land, but the overlying sandstone and calcareous grit show that the general conditions were the same as before. The shaly beds contain a considerable amount of phosphate of lime, evidently derived from the organisms which were decomposing on the sea-floor, and glauconite grains are also common. From these facts I should infer that these beds were slowly accumulated in comparatively clear water, to which fine mud was only occasionally carried by the currents.

The overlying mass of calcareous sediments, more than 1500 feet in thickness, "marks a continuous sinking of the sea-bottom, on which there gathered organic and chemical deposits almost free from terrigenous material. It further shows that this condition of things continued for a prodigiously long period, which in palæontological chronology, as indicated by the contained organisms, lasted from Lower Cambrian to [perhaps] Lower Silurian (Ordovician) time. The main part of this thick series of deposits appears to be derived from the calcareous and siliceous organisms of the plankton and of the animals that fed upon the rain of these organisms that fell upon the bottom" (*op. cit.* p. 370).

The condition of the larger fossils in these Cambrian limestones shows that they must have lain for a long time on the sea-floor and must have suffered greatly from slow decay and solution before they were protected from further decomposition by a covering of the calcareous ooze. The shells are generally imperfect and seldom show the external markings; the Lamellibranchs, though often found with attached valves and in their natural position, are yet often so imperfect that they have clearly suffered much from solution before complete embedment.

In the case of the curious Gasteropod *Maclurea*, which has a large, massive, shelly operculum, the opercula of one species are abundant in a certain set of beds while the shells belonging to them have not been found. Again, the outer walls and the septa of the chambered Cephalopoda have in most cases been largely and sometimes wholly destroyed, so as to leave only the thick column of the central siphuncular portion of the shell.

These facts "seem to indicate that the accumulation of the calcareous mud in which the fossils were embedded was so slow that there was time for the solution of part of the organism before the whole of it was covered up." . . . "As further evidence of the great amount of solution that took place upon the old sea-floor, numerous layers of detached nodules and even continuous sheets of chert, can be seen to have been formed in the calcareous muds before their compression and consolidation." Sponge spicules have been found in some of these cherts, but it is very probable that Radiolaria contributed largely to their formation, though no remains of them can now be recognised.

Lastly, it should here be noticed that this Cambrian sea was tenanted by many different classes of invertebrate animals, including Sponges, Cystidea (primitive Echinoderms), Annelida, Brachiopoda, Lamellibranchiata, and Gasteropoda, while in the later part of the period forms of Cephalopoda belonging to the highest class of Mollusca make their appearance.

B. *Physical Geography of the Period*

From the facts recorded in the preceding pages it is possible to draw some general inferences with respect to the physical geography of the British region during this period.

In the first place, it seems as if, in this region at any rate, land and sea had become less interlocked and more differentiated than they had been in the previous Archæan era. In the place of shallow, more or less land-enclosed, and nearly fresh-water seas, the most highly developed inhabitants of which seem to have been soft-bodied worm-like creatures, the Cambrian sea appears to have been more open, and in its northern part certainly much deeper, than the corresponding part of the Eparchæan sea. Not improbably it was appreciably more saline, and it was tenanted not only by numerous Annelids, but also by many other classes of animals which had both hard and thick shells.

When, however, we try to ascertain the relative positions of land and sea in Cambrian times, we are obliged to confess that the data on which we have to rely are not sufficiently numerous to warrant any attempt to restore the exact geography of either Lower or Upper Cambrian time. The areas in which the Lower Cambrian rocks are exposed are so few, and some of them are so small, that the stratigraphical data for delineating coast-lines are at present quite too incomplete; there is more evidence for the extension of the Upper Cambrian sea, but at the same time less evidence for the exact position of the land areas during this later portion of the period.

Lower Cambrian Time.—It is necessary, therefore, to consider first the physical conditions of Lower and Middle Cambrian time, during which the sea was tenanted by the Olenellian and Paradoxidian faunas, and coarse arenaceous deposits were formed in many places.

Wherever the base of the Cambrian System is exposed in Britain it has been found that the lowest beds are conglomerates or pebbly quartzites which were originally sandstones, and from this fact we may infer that large areas of Eparchæan land were undergoing detrition and destruction during the time when the *Olenellus* fauna prevailed in the sea. Some portions of this land were probably quickly reduced to the condition of islands, but other parts remained to form the main tracts of Cambrian land.

There are two areas which afford some definite evidence of the position of the principal land-tracts in the British region, Lower and Mid-Cambrian time. These are North Wales and Brittany.

We have seen that in North Wales there is a rapid diminution in the thickness of the series when it is traced north-westward through Carnarvonshire, while still consisting mainly of conglomerates, sandstones, and flagstones; and the further fact that if any representative of the Cambrian exists in Anglesey it is not older than the Tremadoc Beds gives positive evidence of land in that direction.

Hence we may conclude that in early Cambrian time a line of coast trended from N.E. to S.W. through Carnarvon and along the flank of the main Archæan ridge through Llyn Padarn and Llanfillyn, the area to the west of this ridge not sinking below the sea-level till the time of the Lingula flags.

Anglesey, therefore, was part of a land-area which must have been of considerable size in order to furnish all the materials which compose the Harlech Beds of Merioneth. There must also have been land to the south-west outside St. David's Head, since the source of the arenaceous materials of the Caerfai and Solva Beds cannot have been far away; and in spite of the continuous subsidence which permitted the accumulation of over 4000 feet of such material, it is evident that the sea was always a shallow one, in which sand was the prevailing deposit.

The other area where there seems to be good evidence of the contemporaneous existence of land is Brittany. If the interpretation of the stratigraphical facts given on p. 53 is correct, and if the lower beds of the Cambrian are overlapped by the "grès felspathique" in the north of Brittany and of Normandy, then it is evident that the northern Armorican area, including the Channel Isles and part of the Cotentin, was land in early Cambrian time. It is probable also that this land included all the western part of what is now the English Channel.

We have at present no evidence from which to judge how much farther to the north and west this land extended, but it is quite possible that it included the Archæan areas of the Lizard in Cornwall, and of the Start in Devon, and that it stretched for a considerable distance westward over the shallow part of the Atlantic to the south of Ireland, so as to be continuous with the land which supplied the materials of the Pembrokeshire Cambrian. This land may have included a large part, if not the whole, of Ireland, but since no rocks of Lower Cambrian age have yet been recognised in any part of that country, there is at present nothing to tell us how much of the Hibernian region was land and how much was sea in the early part of Cambrian time.

When, however, we pass to the N.W. of Scotland we find ourselves once more in presence of a basal arenaceous deposit, resting on a plane of marine erosion, and evidently formed in a shallow sea under the influence of currents, which had completely sorted out the quartz-grains from the other minerals in the Torridonian and Hebridean rocks whence the supply of material was derived.

As Mr. Horne has remarked, "It is obvious that during the interval which elapsed between the deposition of the Torridon sandstones and Cambrian quartzites, the former were thrown into a series of gentle folds ; a vast thickness of them was then removed, so as to expose the Lewisian rocks over wide areas, and the surface of the region was reduced to a fairly uniform plane" (*op. cit.* p. 364). We must therefore suppose that during this interval the whole region had been raised into land, and that in course of time a reverse movement set in which gradually carried the borders of this land beneath the waters of a Cambrian sea.

There remains, however, the important question, From which direction was this land invaded by the sea? in other words, what was the trend of the Cambrian shore-line and in which direction lay the land which continued to supply the sand? Mr. B. N. Peach has answered both these questions in the Memoir above referred to (p. 369), but with his views I find myself unable to concur. Referring to the basement-plane of erosion, he remarks : "Upon a portion of this plane which was being subjected to earth-stresses applied in a north-west and south-east direction, and thus at right angles to those which plicated the Lewisian rocks, the Cambrian coast-line was determined with a north-east and south-west trend. South-east from that shore the Cambrian strata were deposited in a continuously deepening ocean."

Such a statement is remarkable because no stresses coming from the south-east are described as having occurred either in pre-Cambrian or Cambrian time. No evidence that the deposition of the Cambrian quartzites was preceded by great pressures from any direction is given in the Memoir ; the gentle folds mentioned by Mr. Horne appear from his diagram on p. 364 to strike from north to south, the beds rolling over from west to east ; and all the powerful thrusts from the S.E. are referred to a post-Cambrian date, so that the trend of a Cambrian shore-line could not possibly be determined by them.

The stratigraphy of the Cambrian rocks as described in the Memoir above quoted does not seem to afford any very clear indication of the direction in which the land lay. The two zones into which the Quartzite group has been divided occur throughout the whole area, and it is expressly stated that outliers of the Lower Quartzites occur far to the west of the main mass, so that the whole formation must originally have extended far to the westward, and apparently without material change.

Mr. Peach does not mention any evidence of the thinning out of the basal beds in any direction, but he does record the incoming of beds of shale toward the south and S.W., whence he infers that "the mud-line was occasionally reached in that direction." The natural inference from this is that the land lay in an opposite direction, *i.e.* toward the north or N.E. ; an inference which finds some confirmation in the fact that Mr. Clough assigns a thickness of 330 feet to the Lower Quartzite in Skye, whereas in Assynt and farther north its thickness is given as not more than 200 feet, and sometimes less.

I am quite prepared to admit that neither of these facts furnishes a strong basis for geographical restoration, but they seem to indicate that the sea deepened southward. It will be remembered that this seemed also to be the case of the preceding Torridonian sea, and there is therefore some justification for concluding that the general trend of the coast-lines before the time of the Caledonian orogenetic stresses was from west to east. It will be seen in the sequel that the peculiarities of the Middle and Upper Cambrian faunas afford striking confirmation of the truth of this conclusion.

Upper Cambrian Time.—The probable position of the land-areas which existed in the earlier part of Cambrian time having been indicated, it remains to describe such changes as seem to have taken place during the later part of the period. Owing to the movement of subsidence which appears to have been continued throughout the whole of the period, these changes were all in the direction of a decrease in the size of the land-areas and an increase in the spread of the sea over the Franco-British region.

There is only one district where we have evidence of the persistence of a coast-line through nearly the whole period, and that is the Anglesey-Carnarvon area. From the slow retreat of this coast-line, considered in connection with the great thickness of the Cambrian deposits in Wales, we may infer that the Cambrian land was here very steep and lofty. In all probability Anglesey is the remnant of a rocky promontory which was itself the eastern termination of a mountain range, and it is very likely that this range had a general east and west direction. If this were so, and if a similar promontory projected eastward from Atlantic land into Brittany, then the mass of the Welsh Cambrians was accumulated between the horns of a very wide bay.

The extreme north and west of Brittany does not seem to have been submerged till the epoch of the Lingula flags, and even at that time the land which furnished the conglomerates of Bréhec and Cap la Chévre near Brest cannot have been far away. The Bray series, on the other hand, though lying so much farther west, could not have been formed in the close proximity of land. Consequently we may infer that the land at the back of the great bay above indicated was low, so that much of it may have been covered by the sea of the Lingula flags.

As to the eastward extension of the Upper Cambrian sea, we know that it stretched across the central parts of England, and have seen that there is good reason to believe that it passed across our eastern counties and the North Sea over Belgium and Northern France. We know, too, that it spread in a northerly direction over Westmoreland, Cumberland, and the Isle of Man, the prevalent deposit in that area having been originally a fine mud, now indurated and cleaved into slate.

About 200 miles north of the Isle of Man we come to a region where the Upper Cambrian series is represented by a deposit of a very different kind. This is the Durness limestone, of which some part may be Middle Cambrian, but for the greater part seems to be of Upper Cambrian age. Hence it is clear that by the middle of the Cambrian period all the land within the limits of the North British region was submerged and covered by a deep sea in which a great thickness of fine calcareous ooze or mud was slowly accumulated. It is, however, the peculiar fauna found in these limestones, and its strong affinity with that of the American "Calciferous Sandstone," which is of special importance in considering the geographical connections of land and sea at this epoch.

On this subject Mr. Peach makes the following significant remarks: "Not only are the fossils identical on the two sides of the Atlantic, but the sediments in which they have been preserved present a remarkable similarity, as if the North American and Scottish Cambrian rocks were deposited under similar, if not identical, physical conditions, and as part of one and the same geological and zoological province" (*op. cit.* p. 376).

Even the Sail Mhor group, the base of which is about 1000 feet down in the limestone series, contains several fossils closely resembling species in the "Calciferous Sandstone," which is the American equivalent of our Tremadoc slates. It is, however, higher up, in the Croisaphuill group, that fossils are most abundant, and there can be no doubt that the fauna of this is of the same age as that of the Calciferous Sandstone. Some of the genera are peculiarly American and are not known elsewhere in Europe, such as the Lamellibranch *Euchasma*, the Gasteropod *Maclurea*, and the

Cephalopod *Piloceras*; while many of the Scottish shells seem to be specifically identical with those in the American rocks.

These facts increase the probability of the suggestion which Mr. Peach made many years ago,[1] "that some old shore-line or shallow sea must have stretched across the North Atlantic or Arctic Ocean along which the forms migrated from one province to the other, and that some barrier must have cut off this area from that of Wales and Central Europe." If he were writing at the present day Mr. Peach would doubtless express his meaning in somewhat different language, for the Scotch area may have been actually part of the American zoological province, and the barrier to the further migration of the American species may have been nothing more substantial than a sea which was unfavourable to their existence.

We seem, indeed, to have actual evidence of such a sea in the unfossiliferous states of Cumberland and the Isle of Man. There must have been some effective cause for the lifelessness of this sea, and when we consider that the similar sediments of the Tremadoc series in Wales are fairly fossiliferous, the cause can hardly have been the mere amount of sediment in suspension. It is quite possible, however, that this muddiness was the cause which prevented the fauna of the Durness limestone from making its way into the English and Welsh region, for the creatures living at the bottom of clear and deep water are never the same as those living on the muddy or sandy floor of a comparatively shallow sea.

The differences between the Welsh and Scotch faunas is very great, and there is the further remarkable fact that the Scotch fauna differs as much from that of the contemporaneous deposits in Scandinavia as it does from the Welsh; so that this American fauna was in some way prevented from spreading eastward into the Scandinavian region, just as it was prevented from reaching southward into England and Wales.

I think, therefore, that Mr. Peach's suggestion may be interpreted to mean that a tract of land stretched across the North Atlantic throughout the whole of Cambrian time, so that the sea over the north of Scotland was actually part of a North Atlantic province which extended from Canada to the neighbourhood of Iceland. At the beginning of the period the southern shore-line of this northern continent was evidently not far away from Sutherland, but as time went on and the subsidence continued, this shore retreated northward, and the sea over Sutherland became deeper and deeper. At the same time whatever fauna had established itself in the deeper water off the southern coast of this land would naturally spread to the eastward and westward as conditions became suitable for it, and it

[1] *Address to the Roy. Phys. Soc. Edin.*, 1886, p. 7.

must always have been easier for a fauna to spread a great distance between the same lines of latitude than between lines of longitude, which would intersect different climatic zones.

The probability of this being the correct explanation is greatly increased by the fact that such a land-tract would only be a continuation of that which American and Canadian geologists have reconstructed as existing in North America at this period. Mr. Walcott has published sketch-maps of North America showing the probable position of the land-areas at three successive epochs of Cambrian time. That of their Acadian epoch (Middle Cambrian) shows land having a north-easterly trend from the centre of the present continent to the Labrador coast, but in Upper Cambrian time (Olenidian) the coast had retreated northward and the diminished land-area formed an irregular tract extending from Central Canada eastward through the provinces of Ontario, Quebec, Ungava, and Labrador, with an indefinite prolongation into the North Atlantic. Consequently, we have only to extend this prolongation into Icelandic and Scottish waters to obtain a satisfactory explanation of the Scottish Cambrian fauna.

CHAPTER IV

THE ORDOVICIAN PERIOD

THE rocks of this system are exposed over much larger surface-areas than those of the Cambrian, and there is also more evidence of their subterranean connections, so that we have a better knowledge of the actual and original extension of the Ordovician than we have of the Cambrian rocks. Further, the Ordovician deposits are more fossiliferous than the Cambrian, and by means of the Graptolites, which are generally abundant, their successive stages and zones can be much more accurately classified.

The stratigraphical data which have thus been gradually accumulated by geological and palæontological researches prove that the complete system has a wide extension over England, Ireland, and Scotland, and consequently that a very large part of the British region was submerged beneath the Ordovician sea ; so much of it, indeed, that the continental land of the period may have lain almost entirely outside the western limits of our region.

The primary divisions of the Ordovician system were first recognised in Wales through the combined labours of Professor Sedgwick and Sir Roderick Murchison, and they are still widely known by the names given to them by these pioneers. The succession is naturally divisible into three series, as below :—

3. The Bala and Caradoc series.
2. The Llandeilo series.
1. The Arenig series.

A. *Stratigraphical Evidence*

In order to state the stratigraphical evidence as briefly as possible, and to discuss the conditions under which the successive deposits seem to have been formed, it will be convenient to group the various districts where Ordovician rocks occur into larger areas over which they present a more or less similar facies. Of such facies six may be distinguished under the following names:—

1. *The Carmarthen Facies.*—This is characterised by a considerable thickness of fine sediments, chiefly black shale with little volcanic material. It is found over South Wales and the south-east of Ireland.

2. *The Merioneth Facies.*—This is also one of thick sediments, but has thick intercalations of volcanic rocks, sometimes on one horizon, sometimes on another. It occurs in Central and Northern Wales, Shropshire, Anglesey, and the east of Ireland (Dublin and Kildare).

3. *The Cumbrian Facies.*—Remarkable for the immense thickness of volcanic material of Llandeilo age and the small thickness of marine sediments.

4. *The Scottish Facies.*—Notable for the small amount of sediment deposited over a large part of the area, which includes the whole of Southern Scotland, together with the north and N.W. of Ireland.

5. *The Mayo Facies.*—Strongly contrasting with the preceding by its great thickness and the prevalence of coarse sandstones and felspathic grits.

6. *The Armorican Facies.*—In this the thickness of sediment is not great, and arenaceous rocks generally predominate. It is found in Normandy, Brittany, and Cornwall.

1. The Carmarthen Facies.—It is convenient to begin with this facies because in the typical Llandeilo area the whole system is well developed and the succession of the beds is not complicated by the thick masses of volcanic materials which occur in the more northern parts of Wales. Such rocks, both lavas and ash-beds, occur in Pembrokeshire, but in Carmarthen only a few beds of ash are found. The total thickness of Ordovician sediments in this area has been estimated at from 6000 to 7000 feet, but there is so much duplication by faulting and folding that this estimate is probably excessive and the real thickness may not be more than about 4500 feet.

Recent work by the Misses Crossfield and Skeat, Dr. J. W. Evans, and the officers of the Geological Survey has given us much more information about the succession of deposits both in Carmarthen and in Pembrokeshire, and the subdivisions of the three component series have been established on the more secure basis of graptolitic zones.

In this area the Arenig series seems to follow the Tremadoc in conformable sequence, without any distinct break, but the base of the former is marked by a band of coarse grits and conglomerates, the presence of which indicates that some uplift took place and produced a corresponding increase of erosion on some neighbouring land. The Survey recognises two subdivisions in this series, the *Tetragraptus* Beds (in which *Ogygia marginata* and *Didymograptus extensus* are also commonly found) and the *Didymograptus bifidus* Beds. Both consist mainly of bluish-black shales and mudstones.

The Llandeilo series also has a band of sandstones and grits at the base passing upward into volcanic ash, and succeeded by a thick series of shales with *Didymograptus Murchisoni.* The higher beds consist of mudstones and flagstones, with a band of sandy limestone.

The Bala series is divisible into three groups, which in ascending order are: (1) black shales with *Dicranograptus*; (2) dark thin-bedded limestones, containing an abundant fauna of corals, crinoids, Brachiopoda, and Trilobites; (3) the Slade and Redhill Beds, a set of grey mudstones with bands of sandy limestone and micaceous sandstone.

Passing over to Ireland, we find a similar lithological facies in the counties of Wicklow, Wexford, and Waterford. In that area the Arenig is known as the Ribband series, from its thin alternating layers of hard slate and fine grit. The Llandeilo series consists almost entirely of black shales (or slates where cleaved). The Bala Beds consist of shales and mudstones, with at least one band of limestone.

Recent revision of the Irish Ordovician by the Geological Survey has not only established the above succession, but has shown that the associated volcanic rocks, which had been regarded as contemporaneous, are really crush conglomerates formed out of intrusive sills and dykes of post-Ordovician age.

2. The Merioneth Facies.—In North Wales it is also difficult to estimate the thickness of the Ordovician sediments because of the enormous thickness of intercalated volcanic material, and because the graptolite zones have not yet been completely studied or mapped. The total thickness of sediment is believed to be about 6500 feet, but in addition to this felspathic lavas and ashes occur in all three divisions of the system, and even in one locality amount to a thickness of 5000 feet.

The Arenig series is now believed to rest unconformably upon the Cambrian. The break in time between it and the Tremadoc series below cannot have been very great, and the physical disturbance was not of much magnitude; but there was a certain amount of uplift and curvature, resulting in unequal erosion of the Cambrian sediments, so that the Arenig grits come to lie on different parts of the Upper Cambrian series as they are followed toward the north-west.

The stratigraphical relations between the Tremadoc and Arenig series in the typical areas around the Harlech pericline have not yet been worked out, but in the Arenig mountains two groups or zones have been distinguished by their Graptolite fauna, a lower zone with *Didymograptus extensus* and a higher zone with *D. bifidus.* Both zones can be traced through Merioneth and Carnarvon, but the sediments seem to thin toward the N.W. and rest on lower and lower parts of the Cambrian series, till near Aberdaron they include a coarse grit which contains angular fragments of the local Archæan schists (see map of North Wales, p. 49).

Of the Llandeilo series much yet remains to be learnt. In Central Wales there is a lower zone of black shales with *Didymograptus Murchisoni*, a middle zone of shallow-water calcareous flags full of Trilobites, and an upper set of shales with *Cœnograptus.* These zones probably extend throughout Merionethshire, but in the Snowdon district the lower beds have not yet been found, and if they are really absent, the fact may be attributed either to the presence of volcanic islands which occupied the area to the exclusion of the *D. Murchisoni* zone, or else to the action of some powerful current in the Ordovician sea.

In Anglesey the Lower Arenig zone of *Didymograptus extensus* does not seem to occur, and in Mr. Fearnside's opinion they have been overlapped by the higher zone, to which he refers the grits containing *Nescuretus* and *Orthis* there resting directly on the Archæan complex.

Black slates containing *D. Murchisoni* are also found in Central Anglesey, showing that the sea continued to extend as far in this direction as it did in Arenig time, but in Northern Anglesey both the Arenig series and the *Murchisoni* beds are absent; only the Upper Llandeilo (*Cœnograptus* zone) remains, and has a basal conglomerate which rests directly on the Archæan rocks and contains blocks and stones derived from those rocks.

These facts are interesting as demonstrating the persistence of that tract of high land which had existed throughout the Cambrian period on the N.W. borders of Wales. We see that even Anglesey itself was not completely submerged till the close of the Llandeilo epoch, the renewed subsidence of Ordovician time only causing the beach deposits to creep slowly up on the steep slopes of the sinking land.

The Bala Beds in North Wales consist of sandstones and sandy shales, with limestones in the highest part, the lower limestone characterised by Trilobites and the higher by Cephalopods and Cystoid Echinoderms; the whole series indicating shallow rather than deep water conditions, notwithstanding the fact that the Bala sea had a wider extension than that of Llandeilo time.

It has been stated that the thickness of the Ordovician system in Wales is greatly increased by the volcanic rocks which form part of it. These rocks are partly of an interbedded and partly of an intrusive character, but the intrusive masses are mostly of the nature of sills, thrust into and between the stratified deposits, so that they resemble interbedded lava-flows. Some of them are so thick and extensive that they form imposing mountain slopes and precipices, as in Cader Idris, a view of which is given in Fig. 9, taken from a photograph by Mr. Abraham of Keswick.

Cader Idris (see map, Fig. 7) forms a good example of these volcanic rocks. The lower part of the mountain on the northern side consists of an alternating succession of volcanic tuffs and black shales of Arenig age, with two intrusive sills of dolerite. Above this series lies a great mass of grey columnar eurite (or quartz felsite) about 1500 feet thick. This mass is shown in the foreground of Fig. 9, and at the top of the screes which slope into the little tarn of Llyn-y-Gader. Above it there is another set of stratified tuffs and shales, and the actual summit consists of vesicular dolerite, said by Ramsay to be 500 feet thick, but to be an intrusive sill. It will thus be seen how largely volcanic rocks enter into the structure of the district.

The tuffs and ashes were evidently ejected from a volcano, which probably formed a volcanic island in the neighbouring sea, but Messrs. Cole and Jennings [1] remark that the frequent alternation of shales with the ash-beds shows that the centres of eruption were at some distance from the present mountain, and the absence of actual lava-flows points to the same conclusion. They think that the dolerites belong to the same period of volcanic activity, but that the eurite may be of somewhat later date and may be a lateral offshoot of the same molten mass from which proceeded the felspathic Llandeilo lavas of Craig-y-Llan to the southward. It is quite possible that part of the rising magma forced a lateral passage and formed a sill in the Arenig series of Cader Idris, while the rest of it rose in the throat of the volcano and was poured out in lava-streams, portions of which survive in the lavas of Craig-y-Llan.

The Bala sea spread westward across the Irish Channel and far into the centre of Ireland. Bala Beds, with an interesting series of interbedded volcanic rocks, are exposed on the coast of Dublin at Portraine and Lambay Island. The series of beds there seen, as recorded by Messrs. Gardiner and Roberts, may be interpreted historically as follows :—

[1] *Quart. Journ. Geol. Soc.* vol. xlv. p. 431.

A volcanic vent established itself in the Ordovician sea not far from Portraine and formed a volcanic island, from which many streams of andesitic lava were poured out from time to time. One of these flowed in the direction of Portraine, and its emission was followed by an explosive eruption which strewed quantities of blocks, stones, and fine ash over the surrounding sea-floor. Probably this eruption was only the prelude to the issue of another flow of lava which descended in some other direction. As these explosions and outflows of lava died away, beds of calcareous mud began to be deposited, and various kinds of marine animals found the submarine slopes of the island so favourable to their existence that their remains rapidly accumulated to form beds of limestone. At this time certain corals were so abundant as to form coral-banks, and one of these now appears as the "coral-bed" in the limestone; but it would be quite a mistake to regard it as the remains of a coral-reef in the proper sense of that term, for to such a reef it does not bear the slightest resemblance.

The eastern extension of this North Welsh facies has been left till the last in order to emphasise the importance of the overlap which occurs in Shropshire, an overlap which is comparable to that found in Anglesey. On the Welsh borders in the Berwyn Mountains the complete Ordovician succession is still present, but on the eastern side of the Longmynd the only Ordovician rocks to be found are those forming the local Caradoc series. This series rests unconformably upon the older rocks of the district, Cambrian and Archæan, and is clearly an arenaceous shallow-water formation. At the base are conglomerates and grits containing pebbles of the older rocks, and these are succeeded by a series of shales, flagstones, and sandstones with two or three bands of limestone; many of the beds are full of such fossils as would live in shallow water, especially Brachiopods, Corals, and Trilobites, while Graptolites are rare.

It is clear, therefore, that between the Stiperstones and the basal Caradoc grits of Hoar Edge some 4000 or 5000 feet of strata have thinned out, and if we could replace the rocks which have been removed from over the Longmynd we should doubtless see that the Llandeilo overlapped the Arenig, and the Caradoc series overlapped the Llandeilo. Such an overlap is a clear indication of the existence of land, and in this case the seaward border of the land must have had a very steep slope to the west.

We may also reasonably infer that a few miles farther south-east the Caradoc sandstones also thin out, for we know that at the Lickey Hill in Worcestershire the Cambrian quartzite is covered

Photo *G. P. Abraham, Keswick.*

Fig. 9.—VIEW OF THE NORTHERN SIDE OF CADER IDRIS, SHOWING THE SUCCESSIVE MASSES OF VOLCANIC ROCK WHICH FORM THE PRECIPICES ABOVE LLYN-Y-GADER.

directly by the Silurian without any representative of the Ordovician system.

The absence of the Ordovician at the Lickey, taken by itself, would not have proved the existence of land there in the Ordovician period, because deposits of that age might have been laid down over the counties of Stafford and Worcester, and have been removed during the period of upheaval and erosion that preceded the formation of the Silurian ; but taken with the overlap in the Ordovician of Shropshire, the existence of such land is a fairly certain inference.

3. The Cumbrian Facies.—In the Lake District we find the Arenig series represented by the upper part of the Skiddaw slates, the Llandeilo by the Milburn slates, a thin band containing *Diplograptus dentatus* and overlain by an immense thickness of andesitic and rhyolitic lavas and felspathic tuffs which are believed to reach a total of some 12,000 feet. The higher part of this series may, however, be of Bala age, for the overlying Bala shales and limestones are not more than 350 feet thick.

In this district the physical interest centres in the small thickness of the actual sediments and in the great thickness of the volcanic rocks. At the base there are alternations of slates and tuffs, proving, as pointed out by Mr. Clifton Ward,[1] that volcanic action commenced on the sea-floor and gradually built up a pile of volcanic materials, which eventually rose above the surface of the sea and formed a volcanic island. The following paragraphs are quoted from Mr. Ward's paper :—

"The centres of eruption are difficult to fix upon, as might be expected amongst volcanic remains of such antiquity. The boss of Castle Head, Keswick, almost certainly represents one such centre, and the best developments of lava-flows are all found occurring within an easy distance. . . . What the height of the old Cumbrian volcano or volcanoes may have been it is difficult to estimate, but volcanic deposits were accumulated to a thickness, in parts, of at least 12,000 feet, and the highest beds known are unsucceeded by any conformable series of sedimentary rocks ; hence we know not how much of the products of the old volcano has been lost, and, for aught we know to the contrary, an Etna in size once may have stood where now are the resting-places of quiet lakes."

When volcanic activity had ceased, "a subsidence of the region ensued, accompanied doubtless by much waste of the volcanic material through the agency of atmospheric denudation. Subsidence, however, continued until the old volcano came within the

[1] *Geol. Mag.* 1879, p. 52.

planing power of marine coast-action, and at last there was probably but little of the old terrestrial volcano left above the level of the sea." As the waters gradually crept over the site of the volcanic disturbances, the calcareous sediment, which was being deposited on the surrounding sea-bottom, gradually enveloped and covered the surface of the sinking volcanic area. That this sea covered the greater part of Northern England is known from the existence of Ordovician rocks in Teesdale and near Ingleborough.

4. The Scottish Facies.—The greater part of the southern uplands of Scotland consists of Ordovician and Silurian rocks. The special interest of the area is that it includes three different lithological types or developments of the formation, though these pass into each other by gradual lateral change and intercalation.

So far as the Ordovician is concerned, the area is divisible into three tracts or belts : (1) the southern belt or Moffat type, extending from the Mull of Galloway by Moffat to Melrose, and having a width of from 15 to 20 miles—in this belt the Ordovician only occurs in narrow inlying patches ; (2) a northern belt extending from the north of Wigtonshire to the Moorfoot and Lammermuir Hills—in the west this is from 12 to 15 miles wide, but narrows eastward ; (3) the Girvan area in Ayrshire which is less than 30 miles long.

The Arenig series maintains the same facies throughout the whole region ; consisting partly of volcanic rocks, the base of which is not seen, and partly of Radiolarian cherts and shales, which have a thickness of about 70 feet where they are free from any interbedded tuffs. The volcanic rocks are diabasic lavas, tuffs and agglomerates which seem to be the product of submarine eruptions. The cherts occur sometimes in continuous beds, sometimes as nodules in the shales, and are of red, green, or grey colours.

The Radiolaria, which abound in the cherts, were described by Dr. Hinde in 1890, who considered that the beds represented a fossil "radiolarian ooze" and inferred that they were formed at depths of more than 2000 fathoms. His opinion was adopted by Messrs. Peach and Horne in the Memoir on the Silurian Rocks of Scotland (1899), and consequently they assume that these chert beds are an oceanic formation comparable to the oceanic Radiolarian ooze of modern oceans. From this view I feel compelled to dissent: the Radiolarian cherts were evidently deposited in an area which was so far from land that very little terrigenous material was carried into it, but no inference as to the depth of the sea can be drawn from the presence of Radiolaria (see Chap. I. p. 12). Other objections will be mentioned presently.

The authors of the Survey Memoir consider that the Lower

Llandeilo is represented by a few feet of the highest Radiolarian cherts and mudstones, but the only ground for this view is that over the greater part of the area the succession appears to be continuous. The fact remains that the characteristic Lower Llandeilo graptolites have nowhere been found, though they do occur in Cumberland.

The equivalent of the Upper Llandeilo in the southern part of the area is the Glenkiln shale, a narrow band of black shale, mudstones and cherts, not more than 18 feet thick. In the northern belt, however, these beds thicken out by the intercalation of sandy shales and flagstones, till they are more than 1000 feet thick. The cherts in the black shales are black, those in the mudstones are grey, but both contain Radiolaria like those in the Arenig cherts. Moreover, they do not cease to occur northwards after the sandy beds come in ; and at Tannylaggie, west of Bladenoch, grauwackes and grits are interbedded with beds of Radiolarian chert. Here, therefore, the cherts alternate with fairly coarse terrigenous deposits, clearly indicating an approach to the land which was the main source of supply, as the authors of the Memoir admit. They omit, however, to explain how this association can be reconciled with the oceanic theory, and it seems to me that the facts suffice to disprove Dr. Hinde's contention. In justice to him, however, it should be stated that the stratigraphical details were not known to him in 1890, when he very naturally compared the ancient Radiolarian material with modern deposits.

In the Girvan area there are still greater lithological differences and still stronger evidence of the neighbourhood of land. On the S.E. side of the Stinchar valley the Arenig cherts are succeeded conformably by Upper Llandeilo mudstones, shales and grits, above which is the Glen App conglomerate containing pebbles derived from Arenig rocks. This is accounted for by the succession found only a few miles away on the N.W. side of the Stinchar, where a complete break occurs ; and the Arenig cherts are overlain unconformably by the Kirkland boulder conglomerate ; which passes up into calcareous sandstone. Still higher in the same Glenkiln or Llandeilo series is another and thicker conglomerate, from 500 to 800 feet thick, consisting mainly of well-rounded blocks of volcanic rocks with pebbles of quartz, grit, and chert.

The Caradoc or Bala series is represented in the southern belt by the Hartfell shales, which are there only 100 feet thick ; but as with the underlying beds, so also these shales thicken northwards and westwards by the intercalation of flagstones and sandstones, till in the northern belt they are about 1800 feet, and in the Girvan area they reach 2800 feet. In several places, and especially between the valleys of the Nith and Clyde, the lowest beds are breccias and conglomerates resting unconformably on the Arenig or Llandeilo Beds, a curious superposition which, like that of the Kirkland conglomerate, tells of local volcanic disturbance with probably the formation of volcanic islands. Apart from such local phenomena, however, it is evident from the thickening and increasing coarseness of the arenaceous sediments toward the north-west that an extensive area of land lay in that direction.

The Scottish facies of the Ordovician is found again in the northern part of Ireland. The Moffat type of dark shales and mudstones, of small thickness and yielding graptolites of Glenkiln and Hartfell species, occurs in the counties of Down, Armagh, Monaghan, and Cavan; and in some places lower beds with chert nodules are brought up by sharp anticlinal flexures. This Moffat facies is doubtless prolonged still farther south-west beneath the counties of Longford and Clare, for it recurs round Lough Derg on the borders of Clare and Tipperary.

To the northward, however, near Pomeroy in Tyrone, there is a small area where Ordovician and Silurian strata again come to the surface, and the locality is important because it exhibits a littoral facies of the Bala Beds. No rocks of Arenig or Llandeilo age have been found along this outcrop; they seem to have been overlapped by a set of grits, flagstones, and shales which yield a fauna like that of the highest Bala Beds of the Girvan and Lake districts.

From the latest description of these beds near Pomeroy[1] it appears that their total thickness is about 350 feet, and that they rest unconformably upon the adjacent metamorphic rocks (Archæan). The lowest beds seen are coarse grits consisting of "almost unweathered felspars and micas with abundant angular quartz-chips, which are embedded in a sort of serpentinous paste such as might well be directly derived from the denudation of the hornblendic series or of the mica schist country a little further north." The actual basement bed seems to be a conglomerate.

From these facts it is clear that we are here on one of the shore-lines of the Ordovician sea, and that much of Tyrone, with perhaps parts of Derry and Donegal, was land during the formation of Arenig and Llandeilo deposits to the southward.

5. The Mayo Facies.—In the far west of Ireland, in the southern part of Mayo, there is a great development of Ordovician rocks which, on the whole, are different from those of any other district, though to some extent they resemble the Girvan facies.

[1] See Fearnsides, Elles, and Smith in *Proc. Roy. Irish Acad.* vol. xxvi. p. 97 (1907).

The following brief description of them is taken from the recent papers by Messrs. Carruthers and Muff,[1] and by Messrs. Gardiner and Reynolds.[2]

The actual base has not been seen, but near Lough Mask the lowest beds are coarse conglomerates, the pebbles of which are grits from a source not yet identified. Above these is a band of black shales and Radiolarian cherts, succeeded by coarse quartzose and felspathic grits; a conjunction, be it noted, which practically refutes the idea of such chert beds being deep oceanic productions. All these beds are of Arenig age and are about 1200 feet thick. Near Tourmakeady the Llandeilo is represented by (1) flows of red felsitic lava, (2) pink and white limestones, (3) gritty tuffs and limestone breccias; but farther west this volcanic group is replaced by the Muilrea grits, current bedded red and green felspathic grits with bands of green shales yielding Brachiopods and Trilobites, and having a thickness of about 3000 feet.

These beds pass up into a monotonous mass of grits, which has a thickness of about 9000 feet without a single parting of shale. They are destitute of fossils, but are probably of Bala age. Messrs. Carruthers and Muff suggest that these upper grits, "containing as they do an abundance of angular grains of fresh pink felspar and exhibiting a conspicuous false-bedding and lenticular pebble beds, were accumulated on a land surface under arid continental conditions." They certainly remind one of the Torridonian sandstones and of the felspathic sandstones of Brittany, and they have doubtless been formed from the rapid erosion and detrition of a land consisting mainly of granite and felspathic rocks.

Moreover, south of Killary Harbour there are conglomerates of either Llandeilo or Bala age, the component pebbles being principally of granite, quartz-felsite and quartz-schist, resembling rocks occurring farther south in Galway. Lastly, it should be noted that the total thickness of the Ordovician in this district is over 13,000 feet.

6. The Armorican Facies.—In the north-west of France there is a complete passage upward from the Cambrian to the Ordovician system, and as the rocks which form this passage do not yield fossils, there has been much doubt as to the proper line of division between the two systems. As stated in the previous chapter (p. 53), the tendency of modern opinion is to place the divisional line at the base of the felspathic sandstones, which in Normandy and the N. of Brittany underlie the quartzose sandstones which are known as the "Grès Armoricain."

[1] *Irish Naturalist*, vol. xviii. p. 7 (1909).
[2] *Quart. Journ. Geol. Soc.* vol. lxv. p. 104 (1909).

The following is the succession of the beds found in Normandy, grouped under the heads of the main British divisions :—

			Feet.
Bala series	Green slates with *Trinucleus*		200
Llandeilo series	Reddish sandstones (Grès de May)		500
	Blue slates with *Calymene Tristani*		300
Arenig series	White quartz sandstones (Grès Armoricain)		400
	Pink felspathic sandstones	up to	400

It will be noticed that the total thickness (about 1800 feet) is very small compared with that of the Welsh Ordovician. The felspathic sandstones indicate the near neighbourhood of a land where granitic rocks were subject to erosion, and the land may have lain chiefly to the west of Brittany ; probably it was the same area which appears to have been land in Lower Cambrian time (see p. 59).

The felspathic sandstones in some places overlap the Cambrian on to the Archæan rocks, and in Central Brittany they are absent, having in turn been overlapped by the Grès Armoricain, showing that the Cambrian island was by that time completely submerged. Moreover, in Western and Southern Brittany the felspathic grits are entirely absent and the Grès Armoricain thins southward or is replaced by slates, as if in that direction we passed away from land. At the same time it is probable that during the Llandeilo and Bala epochs a sea of no great depth spread continuously over the whole of the N.W. of France and northward towards England.

Passing now across the Channel to Cornwall we should naturally expect to find a succession that was more or less similar to that of Northern Brittany. It has long been known that rocks of Ordovician age occurred in the south of Cornwall, but the whole district has been subjected to such great earth-stresses, and the rocks are so broken, faulted and plicated, that it is a matter of great difficulty to make out their original succession and the relations of the several groups to one another.

During the last few years, however, the area has been resurveyed by the staff of the Geological Survey, and more accurate knowledge of its general structure has thus been obtained. The main result of this survey was to prove that all that part of Cornwall which lies south of a line drawn from Porth Towan on the west coast through Probus to Veryan Bay consists of rocks which are older than the Devonian, except a small area round Manaccan which includes the conglomerate of Nare Head formerly supposed to be of Ordovician age, but now shown to be the local base of the Devonian system. Another result has been the establishment of a definite sequence in the older Palæozoic series, and the naming of certain rock-groups which are believed to occur in the following descending order :—[1]

Gorran quartzite with *Calymene Tristani* and other fossils.
Veryan Beds : bluish slates with thin beds of limestone, sandstone, and black chert containing Radiolaria.
Portscatho Beds : bluish slates with beds of hard grit.
Falmouth Beds : green and grey slates with layers of fine grit.
Mylor series : banded slates in thin alternating layers of slate and fine grit (quartzophyllades).

No base has been found to this series, and no fossils have been found in the lower part of it, so that it is uncertain whether it is a descending or an ascending sequence. The Gorran quartzite is of Llandeilo age and is comparable with some part of the "Schistes d'Angers" of which *Cal. Tristani* is a characteristic fossil, but it is obvious that the rest of the succession is very different lithologically from that which is seen in Brittany.

From the occurrence of Radiolaria the Veryan Beds have been regarded as belonging to the Arenig series, a reference which is rendered probable by their proximity to beds of Llandeilo age, and by the presence of intercalated pillow-lavas like those occurring in the Arenig series of Ayrshire. At the same time chert beds containing Radiolaria have also been found both in the Falmouth and in the Mylor series, and there is nothing distinctive about the cherts in the Veryan Beds.

So far as the evidence goes it favours the view that the whole succession is of Ordovician age, and that it has been formed in deeper water than the deposits of the same age in Normandy and Brittany. At the same time it must be remembered that the Llandovery series of Brittany includes beds of black chert with Radiolaria, and consequently that some of the Cornish rocks, grouped in the Falmouth and Mylor series, may be of Silurian age.

There is, however, no doubt that the Ordovician sea spread over Cornwall, and probably it had a wide extension both to the east and west of that area ; eastward it probably extended through Belgium and the N.E. of France, as rocks like those of Cornwall occur between Brussels and the Ardennes. These include slates and quartzites referred to the Bala and Llandeilo groups, followed by black graptolitic slates of Arenig age, and still farther north by grits and slates of Cambrian age.

[1] See *Sum. Prog. Geol. Survey* for 1898, and "The Geology of the Country around Mevagissey," *Mem. Geol. Survey* (1907).

B. *Geographical Restoration*

We have seen that in North Wales there is evidence of a break with a certain amount of unconformity at the base of the Ordovician system, and in one direction, at any rate, this involves a very decided transgression of the Ordovician base across the denuded edges of the Upper Cambrian series, although the actual difference of dip is very slight. Mr. Fearnsides has described it as the result of "an early Caledonian earth-wave which has left but little impress upon the dip and strike of the rocks which it affected."

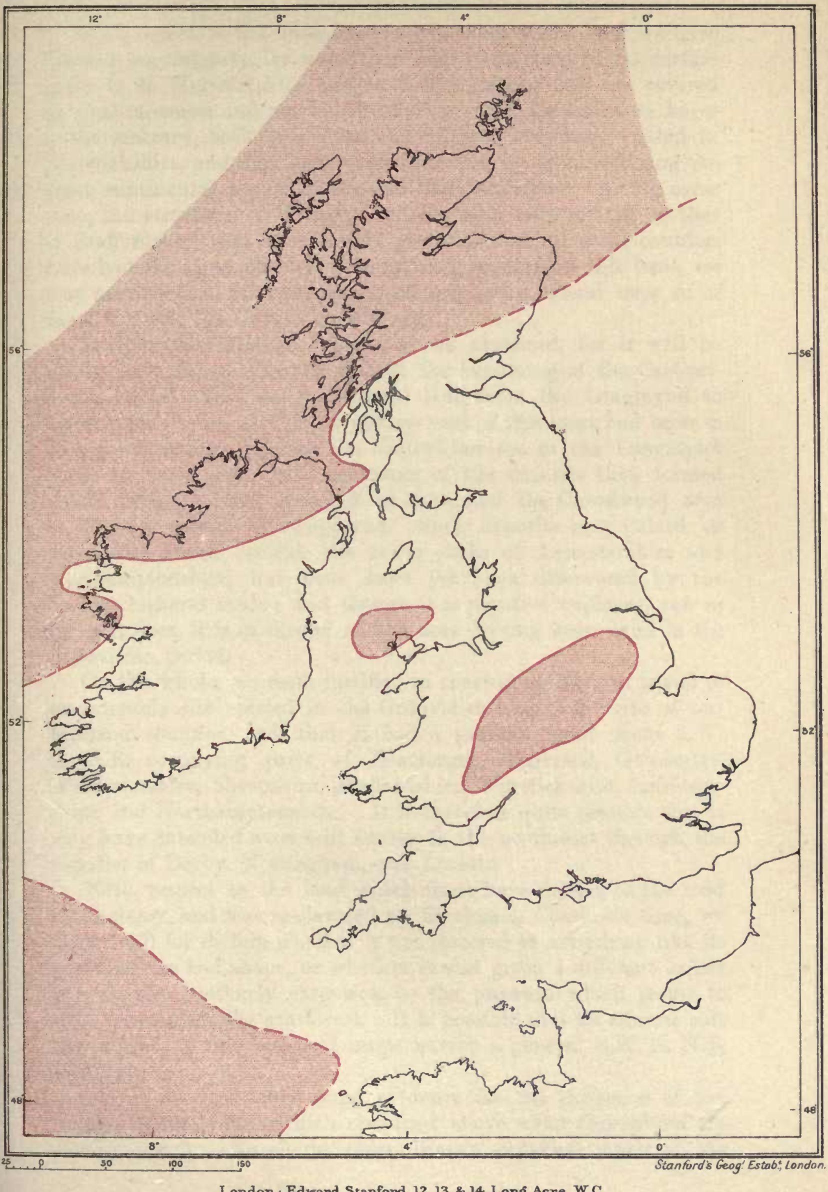
The movement does not seem to have been merely a vertical uplift, but one which ridged up certain portions of the Cambrian sea-floor into land. At the same time its effect was probably felt in the land-areas which had been slowly subsiding through the whole of Cambrian time. The activity of the rivers which drained these lands would be renewed, with the result that sand and grit would be transported far out over the surface of the surrounding Cambrian deposits.

The evidence for the existence of land to the east of Wales over parts of Shropshire and Worcestershire has been given on p. 70, and we have now to inquire how far this land may have extended in southerly and easterly directions.

In the Malvern district there is also an absence of Ordovician rocks, the lowest beds of the Silurian resting unconformably on older rocks; as Malvern is situate on a line of longitude which runs midway between Caradoc and the Lickey, it is interesting and suggestive to find that it represents just such a stratigraphical sequence as we might expect to find if it lay directly between the Shropshire and Worcestershire exposures. It is probable that if a boring was made a few miles west of the Malvern ridge, the Caradoc sandstones would be found below the Silurians and occupying the same position which they hold in Shropshire. Towards Malvern they are overstepped by the basal Silurians, and we may therefore consider the Malvern ridge to be part of the same shore-line which ran northward through Shropshire.

How much farther to the south and S.E. this land extended it is at present impossible to say, for no rocks older than Silurian come again to the surface till we reach the extreme south of Devon, where Archæan rocks are faulted up and do not assist us in the quest. It is probable that its trend was more in a south-westerly direction under Glamorgan and parallel to the anticline which runs from Shropshire to Cardiff, near which place there is an inlying tract of Silurian strata.

Fig. 10.—GEOGRAPHY OF ORDOVICIAN TIME (ARENIG).



London: Edward Stanford, 12, 13, & 14, Long Acre, W.C.

With regard to the north-eastern extension of the land we have likewise no certainty, for when Cambrian rocks come to the surface again in N. Warwickshire and in Leicestershire, they are covered by Coal-measures and not by Silurians, so that, for aught we know to the contrary, both Ordovician and Silurian may have existed in Warwickshire, and may have been destroyed by erosion during the great continental period of the Old Red Sandstone. At the same time, the structure of Warwick and Leicester is so similar to that of Staffordshire that it is highly probable that all these counties have had the same physical history, and, arguing on this basis, we may assume that Silurian strata did originally extend over all of them but that the Ordovician did not.

Another consideration may also be advanced, for it will be shown in a future chapter that at the beginning of the Carboniferous period there was continuous land from the Longmynd to Charnwood forest, and if the eastern part of this tract had been as deeply submerged beneath the Ordovician sea as the Longmynd seems to have been, some remnants of the deposits then formed would probably have been left on or around the Charnwood area as they are round the Longmynd. Such deposits may indeed be eventually found beneath the newer rocks of Leicestershire and Northamptonshire, but none have yet been discovered by the borings hitherto made ; and though it is negative evidence, yet, so far as it goes, it is in favour of the area having been land in the Ordovician period.

On the whole, we seem justified in concluding that an island of considerable size existed in the Ordovician sea on the site of our Midland counties, and that it had a general trend from S.W. to N.E. occupying parts of Glamorgan, Hereford, Gloucester, Worcestershire, Shropshire, Staffordshire, Warwickshire, Leicestershire, and Northamptonshire. It is therefore quite possible that it may have extended even still farther to the north-east through the counties of Derby, Nottingham, and Lincoln.

With respect to the land which must have existed to the west of Anglesey, and was re-elevated at the close of Cambrian time, we cannot tell for certain whether it was restored to something like its previous size and shape, or whether it was given a different aspect and a more southerly extension by the pressure which seems to have come from the south-east. It is possible that its eastern side was ridged up into a coastal range having a general S.W. to N.E. direction.

So far we have only found evidence for the existence of two isolated tracts of land which remained above water throughout the Arenig epoch. No doubt these islands supplied much of the sedimentary material which found its way into the intervening sea and built up the Ordovician system of Wales. We may suppose also that much supplementary matter was furnished by the active submarine volcanoes and volcanic islands which existed in this sea ; for it is evident from the recent descriptions which have been given of the volcanic rocks associated with the Arenig and Llandeilo Beds, that a large amount of fine volcanic dust was ejected from these volcanoes and went to form beds of more or less ashy shale on the surrounding sea-floor.

These sources, however, will not account for the Ordovician sediments of Brittany, Cornwall, and the S.E. of Ireland, and when we remember the peculiar characters and stratigraphical relations of the felspathic sandstones of Brittany, it seems impossible to account for them without supposing the existence of a considerable area of land lying to the west of Brittany and the S.W. of Cornwall. I have therefore ventured to insert such a tract of land in the restoration of the geography of Arenig time which I have attempted in Fig. 10. It must be clearly understood, however, that this map is nothing more than a hypothetical sketch of what may have been the relative positions of land and sea at that epoch. It is merely an interpretation suggested by the facts already known, and may have to be greatly modified by the results of future discoveries.

We are on somewhat more certain ground when we pass to the north of Ireland, and in considering the meaning of the Ordovician sediments of that area we have to remember that in these countries the tracts where the sediments are thickest and most arenaceous are separated from the Cumbro-Welsh area of deposition by a belt in which sedimentation was reduced to a minimum. It is generally admitted that this belt indicates a tract of the sea-floor which was remote from the land-surfaces of the period, and consequently received only small quantities of terrigenous mud and sand. No doubt the water was fairly deep, but there is no reason to suppose that it exceeded 200 or 300 fathoms.

Moreover, this belt of attenuated sediments appears to stretch continuously across both Ireland and Scotland in a S.W. and N.E. direction. It is therefore a fairly certain inference that the materials which compose the Ordovician rocks of Mayo and Northern Ireland and those of the Girvan facies in Scotland were largely derived from land that lay to the north-west of Ireland and of the southern Uplands of Scotland.

In Galway the proximity of this land is indicated by the Arenig conglomerate of Tourmakeady, and by that of later date south of Killary Harbour, the pebbles of the latter having clearly been derived from a land consisting of Archæan rocks with intrusive masses of granite and felsite, like those now forming parts of Connemara, Mayo, and Donegal. At present we do not know how far the Arenig series, or any other part of the Ordovician system, may have extended westward over the Archæan areas of those counties, but it is safe to say that these areas are only small portions of a land which must have had the dimensions of a continent, and probably occupied a large part of the space which is now filled by the North Atlantic Ocean. The enormous thickness of the Ordovician sediments in Mayo, and the fact of their consisting principally of felspathic grits, is sufficient to prove what a large area of land was laid under contribution to construct them.

From the description of the Pomeroy area given on p. 74 it is evident that land existed there during the Arenig and Llandeilo epochs, and that much of it still remained in Bala times, but whether as an island or a promontory is hard to say.

With regard to the Girvan district its history in Ordovician time is less easy to read. The early phase of eruptive activity, when copious lava-flows were poured out from submarine vents, seems to have been followed by a time when little extraneous sediment reached the area and when Radiolaria were so abundant that, in the intervals between the later volcanic explosions, their remains accumulated to form beds of siliceous material, which now appear as layers of chert alternating with beds of mudstone and volcanic tuff.

In Llandeilo time there were evidently actual upheavals of the sea-floor, resulting in local unconformities, and it is possible that the absence of the zone of *Didymograptus Murchisonæ* may be due to a rapid uplift of the whole area in connection with the outbreak of volcanic activity in Cumberland (Borrowdale series). This uplift may also have been one of the first results of the crust-pressure which ultimately produced the great Caledonian folds and thrusts. Again, at the close of Llandeilo time the Benan conglomerate, the conglomerates and grits of the Balclatchie Beds and the actual unconformity of the Bala Beds north of Sanquhar and elsewhere, testify to a further upheaval of the area.

Finally, the great thickness and the prevalence of sand in the Ardmillan series are clear indications of the near neighbourhood of land. Messrs. Peach and Horne describe them as "shore deposits which were accumulated on a gradually subsiding area." It is true that the "subsiding area" might have been a large island, but we must bear in mind that it is not only the Girvan district that gives evidence of the proximity of land; actual unconformities with local calcareous conglomerates occur in the northern belt in the Lowther Hills, and again in the Wrae district north of Peebles. From these facts I think it may be inferred that the uplift at the beginning of Bala time brought the coast-line of the Atlantic continent very near this part of Scotland, and that its shore must have passed from Pomeroy in Tyrone through Derry and Antrim so as to approach the neighbourhood of Girvan.

In this connection, however, we must remember that chert beds like those of the Arenig series have been found along the southern border of the Highlands, not only in Kincardineshire and Forfar but also in Perth, Dumbarton, and the Isle of Arran. In the present state of our knowledge there is nothing to forbid the supposition that the Ordovician sea had a greater northern extension in Arenig time than it had during the later part of the period, and that in Caradoc (= Bala) time the main coast-line passed not very far north of Girvan, running perhaps to the south of Arran and thence north-eastward toward the North Sea. At any rate we have no reason at present to believe that any rocks of Upper Ordovician age occur to the north of this line, for nothing comparable with them has yet been found in conjunction with the black shales and cherts of the Highland border.

To sum up the conclusions at which we have arrived respecting the physical geography and history of the Ordovician period, they may be stated as follows :—

1. That the period opened with a movement which raised much land above the sea-level, partly in the form of separate islands, partly in the form of continental land occupying much of the North Atlantic area.

2. That the general trend of the main coast-line of this Atlantic land was from S.W. to N.E., and that it passed through parts of Ireland and across Scotland to the North Sea ; the actual position of the shore receding or advancing in accordance with alternating movements of the crust.

3. That the primary uplift was followed by subsidence which diminished the supply of terrigenous material, and seems to have been greatest along a tract which passes from Central Ireland across the Irish Sea and through the most southern part of Scotland.

4. That during the formation of the Bala Beds the movements were irregular, some upheaval taking place on the borders of the continental land, while in the central area subsidence carried the sea over parts of the islands which there existed.

5. Finally, that it was a period of great volcanic activity ; volcanic vents being formed and eruptions taking place in one part of the region or another throughout its whole duration.

CHAPTER V

THE SILURIAN PERIOD

A. *Stratigraphical Evidence*

In dealing with the rocks of this period I shall adopt the same plan as in the case of the Ordovician, and consider the evidence under the heads of large areas in which the strata present a more or less different facies or lithological constitution. Of such areas six may be conveniently distinguished, and these may be called: (1) the Welsh; (2) the Salopian; (3) the Northern; (4) the Scottish; (5) the West Irish; (6) the Armorican.

Although the Salopian facies is generally considered to be the typical development of the system, because it was that on which the "Silurian System" of Murchison was established, it is in reality more exceptional than typical of the full development of the formation. I propose, therefore, to take the Welsh area first, since it is there that the lower part of the system attains its greatest development.

The Silurian succession was originally divided into three groups or series, known respectively as the Llandovery, the Wenlock, and the Ludlow series; but recent researches have made it clear that either this nomenclature must be altered, or that the number of such groups must be increased. Thus it has been shown that the Tarannon shales which lie between the Llandovery and the Wenlock series have a much greater importance, both stratigraphically and palæontologically, than had previously been supposed.[1] Again, at the top of the system is a set of sandstones and shales which were classed as "passage beds" into the Old Red Sandstone by Murchison, but are now regarded as part of the Silurian and yet by some are separated from the Ludlow series.

For our present purpose, however, it will be convenient to retain a division of the system into three series, and to group the

[1] See paper by Miss Wood in *Quart. Journ. Geol. Soc.* vol. lxii. p. 644.

subdivisions which have been recognised in Wales and Shropshire in the following manner :—

Ludlow series	Ledbury and Downton Beds. Ludlow Beds.
Wenlock series	Upper limestone and shales. Lower limestone and shales.
Valentian series	Tarannon shales. Llandovery Beds.

1. The Welsh Facies.—In Central Wales the Silurian system has a total thickness of from 6000 to 7000 feet, but becomes thinner as the beds are traced north, south, or east.

The Valentian series seems to attain its greatest development near Rhyader in Radnorshire, of which district an excellent account has been given by Dr. H. Lapworth.[1] The series is there divisible into three groups : (1) the Gwastaden or Lower Llandovery ; (2) the Caban or Upper Llandovery ; and (3) the Tarannon. Both the Llandovery groups consist of conglomerates, sandstones, flagstones, and shales, which were evidently accumulated somewhat rapidly in a shallow sea and in the near neighbourhood of land ; but they are separated by a marked unconformity, so that in this district the Upper Llandovery is of local occurrence and the Tarannon shales overlap it eastward on to the surface of the Gwastaden Beds.

The terrestrial disturbance and uplift which caused this break was, however, of wider extent, for near Builth, S.E. of Rhyader, the Upper Llandovery comes in again and is found to rest unconformably on the inclined surface of the Llandeilo Beds, having evidently passed transgressively across the outcrops of the Lower Llandovery and Bala Beds, which must have been raised above the surface of the sea and again planed down before the deposition of the sandy Llandovery limestone.

Near Rhyader the total maximum thickness of the Llandovery Beds is about 2800 feet, but near Llandovery to the southward their combined thickness is not more than 1500 feet. When followed northward the diminution is rapid and continuous ; in the Tarannon district (Montgomery) their thickness is probably less than 600 feet, and no break is discernible between the lower and upper groups ; in the Dee valley they are represented by 200 to 300 feet of grit and mudstone, and near Conway these beds have shrunk to 150 feet.

From these facts it is very clear that the main source of the Llandovery sediments lay to the south-east, and especially to the east of Radnorshire and Breconshire.

The Tarannon shales are in some respects a great contrast to the variable, irregular, arenaceous Llandovery Beds ; they consist

[1] *Quart. Journ. Geol. Soc.* vol. lvi. p. 67 (1900).

principally of grey shales and mudstones, which were evidently accumulated slowly and quietly in much deeper water. In the typical Tarannon district they have a thickness of no less than 3000 feet, with many beds of coarse grit or sandstone in the central part, and Miss Wood has been able to divide them into four distinct zones by means of the different species of Graptolites which they contain. Such a series can only have been formed during a gradual and progressive subsidence of the area.

So far as thickness is concerned, however, the Tarannon shales diminish in every direction. Northward the decrease is rapid, till near Conway there is merely 300 feet of shale to represent them. Southward it is not so great, for near Rhyader they are probably about 1500; but near Llandovery less than 1000 feet, and beyond Llangadock their outcrop is concealed by the Old Red Sandstone.

Before leaving the Valentian series, mention must be made of its reappearance in Pembrokeshire, where tracts of both Lower and Upper Llandovery have been mapped, the former on the north side and the latter on the south of the long strip of Coal-measures which runs across the county.[1] The outcrop of the lower group lies between Narberth and Haverfordwest, and its thickness is estimated by Mr. Cantrill to be about 2000 feet without reaching the top. The mass of the formation consists of sandstones and mudstones, but the lowest beds are black shales with an impersistent conglomerate at the base varying from 0 to 80 feet in thickness.

To the south of the Coal-measure tract the Lower Llandovery does not occur; but beds of Upper Llandovery age there rest on a much older volcanic series, and have a basal conglomerate of well-rolled pebbles derived chiefly from these volcanic rocks. Hence we may infer that the lower group thins out against a slope of these older rocks, and is overlapped by the upper group, so that there is here a repetition of the overlap observable near Builth in Radnorshire, and evidence that the southern part of Pembrokeshire was land during the formation of the Lower Llandovery Beds.

The Wenlock series of Wales does not require detailed description for the purposes of this volume. In the Central Builth district it consists entirely of shales and mudstones, all more or less calcareous, with a thickness of about 2000 feet. When traced southwards, however, they become increasingly arenaceous, and near Llandeilo they consist of flaggy mudstones with bands of hard yellow sandstone. South-west of this they are overlapped and concealed by Old Red Sandstone.

When traced northward from Radnor into Denbighshire there

[1] See Marr and Roberts in *Quart. Journ. Geol. Soc.* vol. xli. p. 476 (1885), and *Sum. Prog. Geol. Survey* for 1907, p. 44.

is also a similar change, for though the beds consist largely of shales these are not calcareous, and a thick band of felspathic grit or sandstone occurs in the middle of them.

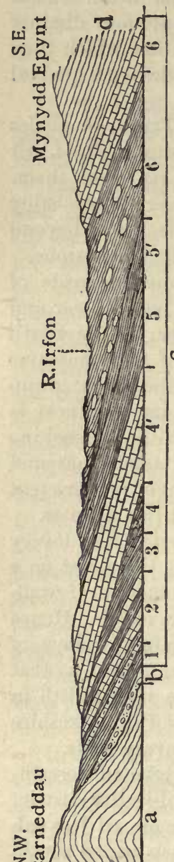


FIG. 11.—SECTION ACROSS THE WESTERN PART OF THE BUILTH DISTRICT.
(From *Quart. Journ. Geol. Soc.* vol. lvi. p. 382, by permission of the Council and of Miss Elles.)
d. Ludlow Beds. *b* = Llandovery Beds.
c (1 to 6) = Wenlock Beds. *a* = Llandeilo Beds.

The chief point of structural interest is the existence of slight discordances in the succession of beds; these were discovered by Miss Elles in the course of her zonal work in the district, and are shown diagrammatically in Fig. 11, which is a copy of the section drawn by her. They occur at two horizons in the series ; thus it will be seen that the zone numbered 4 passes across the surface of zones 4 and 3, so as to rest on No. 2. Similarly zone 6 almost overlaps the upper part of zone 5.

These phenomena can only have been produced by slight uplifts of the central anticlinal ridge above *a*, such movements giving a slight tilt to the sea-floor, and causing the partial removal by waves or currents of the deposits already formed before fresh sedimentation began.

The Ludlow series in the Builth district consists of shales and flaggy mudstones, with a total of about 1500 feet if the Lower Ludlow shales are included. Above these are the Aymestry Beds — massive shelly limestones succeeded by calcareous shales and flagstones (Upper Ludlow shales), followed by the Downton sandstone (40 feet) and the Temeside shales (120 feet), with Lingula cornea and remains of Eurypterid Crustacea.[1] Above these are the flaggy micaceous sandstones, which are locally called tilestones.

It is not in the Builth district, however, that the passage beds attain their greatest thickness ; near Llandeilo in Carmarthenshire they are about 900 feet thick, consisting in the lower part of dark-grey flaggy sandstones, and in the upper part of yellow and red pebbly grits followed by 150 feet of tilestones.

[1] See the Misses Elles and Slater in *Q.J.G.S.* vol. lxii. p. 96 (1906).

There is also a great change in the character of the Ludlow series when they are traced northward, and curiously enough this change is the reverse of what takes place in the case of the Valentian series, for the Ludlow Beds become thicker and more arenaceous northwards till in Denbighshire they consist of sandstones and flagstones, which are believed to be 4000 feet thick without the actual top being visible.

2. The Salopian Facies.— When traced eastward from the Welsh borders into Shropshire and Herefordshire, lithological changes are found to take place in all the divisions of the system.

In Shropshire the Lower Llandovery is altogether absent, and only a thin representative of the Upper Llandovery (30 to 150 feet), with a basal conglomerate and a sandy limestone above, rests unconformably on the Caradoc sandstones. East and south-east, however, there is less diminution of thickness, the Upper Llandovery (May Hill sandstone) being still about 900 feet thick in the Malvern Hills, though consisting almost entirely of sandstone with beds of conglomerate in the lower part. The Tarannon shales also diminish very much in thickness, being only from 400 to 600 feet in Shropshire, and little more than 100 in the Malvern Hills.

The Wenlock series, on the other hand, maintains a considerable thickness to the eastward, notwithstanding the fact that limestones are developed in it, and that the accumulation of such material is generally a slower process than the deposition of shale. In Shropshire there is only one band of limestone (the Wenlock), but in Hereford and Stafford there are two, the Woolhope limestone at the base, and the Wenlock limestone about 800 feet higher up.

The Wenlock limestone, which varies in thickness from 100 to over 200 feet, varies also in its composition, some beds consisting chiefly of shells, some of corals, some being of finer, more compact stone, and others, again, of nodular argillaceous limestone. Mr. Wethered examined some of the limestones from the Malvern and May Hill districts,[1] and found that the compact thin-bedded layers consist chiefly of small ossicles of crinoids, fragments of shells and Polyzoa, valves of Ostracoda, and aggregations of the organism known as *Girvanella*. The shelly beds consist of crinoid stems, shells of Brachiopoda and Mollusca, with fragments of Trilobites, Polyzoa, and Corals. One bed near the base is an oolitic limestone. Near Wenlock, and also at Dudley, corals of the families *Favositidæ*, *Halysitidæ*, *Monticuliporidæ*, *Cyathophyllidæ*, and *Helioporidæ* are sometimes very abundant, but merely as components of limestone beds and not in the form of true coral-reefs; with them Stromato-

[1] See *Quart. Journ. Geol. Soc.* vol. xlix. p. 236 (1893).

poroids of the genera *Labechia*, *Clathrodictyon*, and *Stromatopora* often occur.

Ludlow Beds of the calcareous Builth type extend with little change over Shropshire, Hereford, Worcestershire, and Staffordshire, passing up on the borders of the Old Red Sandstone into the Ledbury shales and sandstones, but succeeded directly by the Old Red Sandstone without the intervention of any tilestones.

The most southerly exposures which can be included in this facies are in Gloucestershire at Tortworth, and again in the Mendip Hills. They are remarkable for the occurrence of lava flows (andesite) and beds of ashy material in the Llandovery Beds, and for the absence of the Tarannon shale. At Tortworth the Wenlock series is only about 600 feet thick, and the Ludlow Beds are also much attenuated, but may originally have been thicker than they now are, for they seem to have suffered erosion before the deposition of the overlying Old Red Sandstone.

We have no knowledge of the existence of Silurian rocks under the Midland counties east of Gloucestershire, Worcestershire, and Staffordshire, but they are known to occur beneath Hertfordshire and Kent, and appear to belong to the Salopian facies. In the south-east of England the Jurassic and Cretaceous strata rest on a platform of Palæozoic rocks, the component members of which are believed to be arranged in a series of more or less parallel flexures striking roughly east and west like those which are known to exist in the north-east of France.

A boring at Ware, in Herts, reached Wenlock Beds at a depth of 796 feet, these beds consisting of limestones, shales, and calcareous mudstones containing many fossils. Quite recently a boring at Cliffe, near Rochester, has disclosed the existence of Silurian rock at a depth of 1037 feet in the condition of a dark-grey indurated clay, which was traversed for 27 feet.[1]

Between these two localities several borings in different parts of the London basin have revealed the existence of newer beds, *i.e.* red and grey sandstones of a Devonian aspect, and in one place of marine Devonian rocks; hence it seems probable that a broad syncline of such rocks underlies the London basin, Silurian Beds cropping out both to the north and to the south of it. Farther north, as stated in the previous chapter, Ordovician and Cambrian rocks come up into the subterranean platform, and probably form part of a broad anticline or a periclinal area comparable to the Harlech area in North Wales. If this is a correct idea of the subterranean geology of the eastern counties, we may infer

[1] See Whitaker in "Water Supply of Kent," *Mem. Geol. Survey*, p. 383 (1908).

that the Silurian strata originally extended over the northern anticline.

3. North of England.—In Westmoreland and the adjacent parts of Yorkshire the Silurian system presents a very different aspect from that of the central parts of Wales and England. In this area the equivalent of the Llandovery Beds is always of small thickness, but the overlying Wenlock and Ludlow series form an enormous mass of sedimentary material with a total thickness of over 12,000 feet.

The Valentian series is represented by two bands or groups of graptoliferous shales, the Skelgill shales and the Browgill Beds, their combined thickness being only from 250 to 400 feet, and the greater thickness being in the south-east near Sedbergh.

It was formerly supposed that these beds were unconformable to the underlying Bala series, but Dr. Marr has shown that there is really no unconformity, the appearance of one being due to the existence of a persistent fault-plane coinciding with the strike of the beds. At the same time the passage is not a gradual one, for a complete change of fauna takes place within a few feet of shale, so that some physical change must have taken place during the deposition of this small thickness of shale. Most probably the change was a general uplift of the area, not sufficient to bring any part of it above the sea-level, but rapid enough to check deposition.

The easterly thickening of the beds is also noteworthy; Dr. Marr has suggested that the increase of thickness was in the direction of the source of supply, and may be taken as an indication that land lay to the east or S.E. of Sedbergh.[1] This view is to some extent confirmed by the sections which are found still farther S.E. between Ingleborough and Settle. Here there are no shales like those of Sedbergh, and there appears to be really an unconformity between the Ordovician and Silurian strata.

The exposures have been described by Professor Hughes,[2] and the most important one is near Austwick, where a calcareous conglomerate about 10 feet thick rests on Bala mudstones, and consists of pebbles and angular fragments up to 8 or 10 inches across of various rocks derived from the "Green Slates" or Borrowdale series. This conglomerate is overlain by a thin bed of calcareous mudstone which is almost entirely composed of fragments of Trilobites (see also Marr, *Geol. Mag.*, 1887, p. 35).

At Horton, in Ribblesdale, neither bed is found, and it is doubtful whether any representative of the Valentian exists at that locality. The facts suggest an uplift of the whole area, which

[1] *Quart. Journ. Geol. Soc.* vol. xliv. p. 718 (1888).

[2] *Mem. Geol. Survey* and *Proc. Yorks. Geol. Soc.* vol. xv. p. 360 (1905).

raised parts of it into dry land and converted other parts into submarine banks, over which hardly any deposition took place (see Introduction, p. 5). If we could strip off the Carboniferous limestone, which covers the Silurian rocks to the east and S.E. of Settle, we might find sections showing a much greater unconformity between the Silurian and Ordovician systems.

Passing now to the equivalents of the Wenlock series in Westmoreland, we find them to be a succession of sandstones, flagstones, and mudstones, which have a thickness of about 2000 feet if the Coldwell grits are included. These arenaceous sediments are indicative of land at no great distance.

Lastly, the Ludlow series is divisible into four sub-groups, each having a considerable thickness ; these are in descending order :

	Feet.
Kirkby Moor flagstones	2000
Bannisdale Beds	up to 5000
Coniston grits	4000
Coldwell flags	1500

Arenaceous material preponderates throughout, only the Bannisdale Beds including subordinate beds of shale, and the actual summit of the formation is not seen, so that the total thickness may originally have been considerably greater. The sandstones are mostly fine grained, but a band of coarse grit occurs in the Coniston grits near Sedbergh.

4. The Scottish Facies.—Silurian rocks occupy a large area in the south of Scotland, and throughout the wide southern belt, which extends from Wigtown to Berwick, they exhibit a facies which is not very different from that of Westmoreland ; but the Valentian as a whole is much thicker, and gradually changes into a series which resembles the Llandovery type.

In the southern belt the Birkhill shales (100 feet thick) represent the Skelgill shales, and rest conformably on the Hartfell shales of the Ordovician. They pass up, however, into a set of flagstones, grits, and shales, which reach a thickness of 3000 feet, and are known as the Gala Beds. In the Girvan area the Birkhill shales have expanded into a series of conglomerates, sandstones, mudstones, and shales, with a maximum thickness of about 1000 feet, but the Gala Beds have at the same time decreased in thickness to about 1700 feet, so that in that district the Valentian as a whole is only 2700 feet in thickness.

The conglomerates of the Girvan area occur on three horizons, one at the base of the Valentian, one a little higher up with a marked unconformity, and the third near the top of the series. The lowest or Mullock Hill conglomerate is described by Professor

Lapworth as a purplish sandstone containing rounded pebbles and boulders of quartz, granite, felstone, and other igneous rocks. Its thickness is about 70 feet, and it passes up into red sandstones. There is no evidence of actual local unconformity at its base, but the sudden change from laminated mudstones to a coarse conglomerate, and the great alteration in the aspect of the fauna, are proofs "of a complete modification of the physical features of the neighbouring sea-bed between the periods of deposition of these highly dissimilar sediments."[1]

In another part of the area, however, there is a decided break in the sequence ; the Mullock Hill Beds are absent, and a higher group (the Newlands or *Pentamerus* grits) develops a basal conglomerate, which lies directly and unconformably on the local top of the Ordovician system. This conglomerate is 50 to 60 feet thick, and consists of well-rounded boulders and pebbles varying from an inch to a foot in diameter, embedded in a coarse sandy matrix of a dark-green colour. The stones include pieces of granite, felstone, quartz, jasper, shale, and grauwacke. Still higher in the same series is another band of quartz-pebble conglomerate, showing that land was still under erosion at no great distance, and that the sea was traversed by strong currents capable of rolling good-sized pebbles along its floor.

The Wenlock Beds are well developed in the southern belt, and are lithologically like those of Westmoreland, with a thickness of 1000 to 1500 feet. They are found again in Lanark and the Pentland Hills, where they are over 2000 feet thick, and contain some massive sandstones and grits. In Lanark they are succeeded by red and green Ludlow shales, which are overlain by quite a different set of beds—red and yellow sandstones and green shales, with a band of conglomerate in the higher part consisting entirely of quartz pebbles. These beds represent the Welsh Downton and Temeside Beds, but are no less than 2800 feet thick, and have yielded a remarkable assemblage of fish and Eurypterid Crustacea.

The Scottish facies of the Valentian and Wenlock series is found again in the northern parts of Ireland, where large parts of the areas originally mapped as "Lower Silurian" (*i.e.* Ordovician) have proved, on revision, to be of "Upper Silurian" age. They are chiefly equivalents of the Birkhill shales and the Gala group, but in Louth there are rocks with Wenlock fossils which are comparable to the Riccarton group. Recent researches have shown that similar rocks probably underlie the whole of Central Ireland.

5. Western Facies.—The western parts of Ireland exhibit

[1] Lapworth in *Quart. Journ. Geol. Soc.* vol. xxxviii. p. 623 (1882).

one of the most interesting facies of the Silurian system, because it is in that direction that we seem to be approaching continental Silurian land. It is only recently, however, that the relations of the Ordovician and Silurian rocks in that region have become better understood, and much work still remains to be done before our knowledge of them is anything like complete.

Beginning in the south, we find a great development of Silurian rocks in Kerry, north of Dingle Bay, a thickness of probably 6000 feet being exposed, though the base is not seen and the summit is uncertain. They consist chiefly of calcareous flagstones, with some shales and many bands of contemporaneous volcanic rocks. They include representatives of the Valentian, Wenlock, and Ludlow series, and they pass up into the Dingle Beds, which are probably partly of Silurian and partly of Devonian age.

As to the conditions under which the Silurian series of Kerry was formed, Messrs. Gardiner and Reynolds write as follows:[1] "The land during the deposition of the Silurian rocks could not have been very far off: for the Silurian sediment found here points to a shallow sea, or to the proximity of land. Even when coral life abounded, the rock in which the corals are now preserved is never a pure limestone, but always of a very arenaceous character, though the corals are preserved not in broken fragments, but in layers of growth. Moreover, layers of conglomerate are found in places throughout the series which show that the volcanic beds in the neighbourhood were being continually denuded. They also point to the former presence at the surface of rocks now not seen in the neighbourhood, for granitic pebbles sometimes occur."

The same observers remark that the thickness of the volcanic material is greater in the southern part of the area, and infer that the volcanic vents lay in that direction. Probably they were volcanic islands. The mainland from which the arenaceous sediments came lay in all probability to the west and north-west of the Dingle promontory, but there may also have been land to the southward.

In Mayo and Galway there is a still more interesting series, for there not only is the base of the Llandovery exposed, but it is found to pass across the edges of the Ordovician strata very rapidly southwards so as to rest on the crystalline schists of Connemara. For the latest information about this district I am indebted to Mr. R. G. Carruthers of the Geological Survey, and to the account of the succession contributed by him and Mr. H. B. Muff to the *Irish Naturalist* for January 1909.

In Mayo, north of Killary Harbour, the Llandovery rests on

[1] *Quart. Journ. Geol. Soc.* vol. lviii. p. 265 (1902).

Arenig Beds, but south of that long inlet it lies directly on the Archæan schists, its base being a breccia consisting of fragments of schist and angular lumps of quartz. A small thickness of barren grits is succeeded by calcareous grits containing Brachiopoda of Upper Llandovery species, and followed by a massive conglomerate consisting mainly of rounded pebbles and boulders of quartzite. To this succeeds a thick series of coarse grits alternating with green sandy slates which have yielded Graptolites of Wenlock species ; these beds may be about 2000 feet thick. Finally, the Ludlow series is represented by the Salrock slates, dull red and green slates with a thickness of more than 3000 feet.

From this succession it is clear that the continental conditions indicated by the remarkable mass of felspathic sandstones, mentioned in the previous chapter (p. 75), continued till Upper Llandovery time, when the border of the western land once more sank beneath the sea. Also that part of the new coast-line lay to the south of Killary Harbour, though in all probability Connemara was part of a promontory projecting eastward into the Silurian sea, the main coast-line lying to the westward of Killary, and possibly passing through the northern part of Mayo.

6. Armorican Facies.—No definite Silurian area has yet been recognised in Cornwall, but fossils of both Wenlock and Ludlow age have been found in lenticles of crushed limestone and calcareous slate on the coast between Nare Head and Dodman Point. Though probably not exactly *in situ*, but connected with a plane of overthrust, they are sufficient to indicate the existence of Silurian rocks within the Cornish area.

In Brittany the Silurian comes into some of the east and west folds which traverse the country, and is represented by a series which ranges from Llandovery to Ludlow, in which black shale is the predominating material. The total thickness is only a few hundred feet, consisting principally of graptolitic and siliceous shales, the latter containing layers of Radiolarian chert ; there are also Pteropod shales and nodular Orthoceras limestone, the whole being a comparatively deep-water facies of the formation. There is every reason to suppose that these deposits covered the whole of Brittany and Normandy, spreading northwards into Cornwall and eastwards into Central Europe.

B. *Physical Geography of the Period*

Having in the preceding pages set forth the evidence furnished by the Silurian rocks as to the conditions under which they were accumulated, let us now review this evidence and endeavour to interpret its geographical significance.

Considering first the system as a whole, the relations of its component groups to one another, and to the older rocks, three general conclusions seem to be warranted by the facts :

1. That the period was ushered in by crust movements which raised parts of the region into the condition of land, one of these areas being partly within and partly outside the extreme west of Ireland, another extending from the borders of Wales over part of England, where land had existed in Ordovician time.

2. That the English area continued to be in an unstable condition throughout the period, epochs of subsidence and upheaval alternating with one another.

3. That the period closed with a slow general upheaval of the whole region and a gradual sitting up of all the areas in which sediments had been deposited.

We may now confine our attention to the lowest or Valentian part of the system, and here we find that the recorded facts furnish good evidence of the varying depths of water and distance from contemporaneous land. The areas where sedimentation was least, and which were consequently the most distant from land, are—Brittany, the northern part of Wales, the Lake District, the south of Scotland, the eastern and central parts of Ireland. On the other hand, conglomerates and sandstones indicative of shallow water and nearness of land occur in South and Central Wales, Central England, the Girvan district, and in the far west of Ireland.

Let us begin with the Welsh border district and consider the position and extent of the land which must have been formed by the initial uplift in Western and Central England. That this uplift was of considerable amount is shown by the disposition of the Ordovician and Llandovery Beds in the Builth district and around the Longmynd area. There is every reason to suppose that both these areas sank beneath the Bala sea, but the absence of Lower Llandovery, the small development of the Upper Llandovery and of the Tarannon shales in both areas, as well as the complete unconformity of the Valentian Beds to all the older rocks, are points of great significance.

The facts will be better appreciated by reference to the map, Fig. 12, from which it will be seen that the ridge of Llandeilo Beds near Builth, and the small exposures of Archæan rocks near Kington, are almost certainly isolated exposures of a buried ridge of such rocks extending southward from the Shelve and Longmynd district of Shropshire. Moreover, it will be seen that this partially exposed ridge had a further indefinite extension to the N.E. beyond the Longmynd area, isolated exposures of the Longmyndian and Uriconian rocks occurring at Haughmond Hill (N.E. of

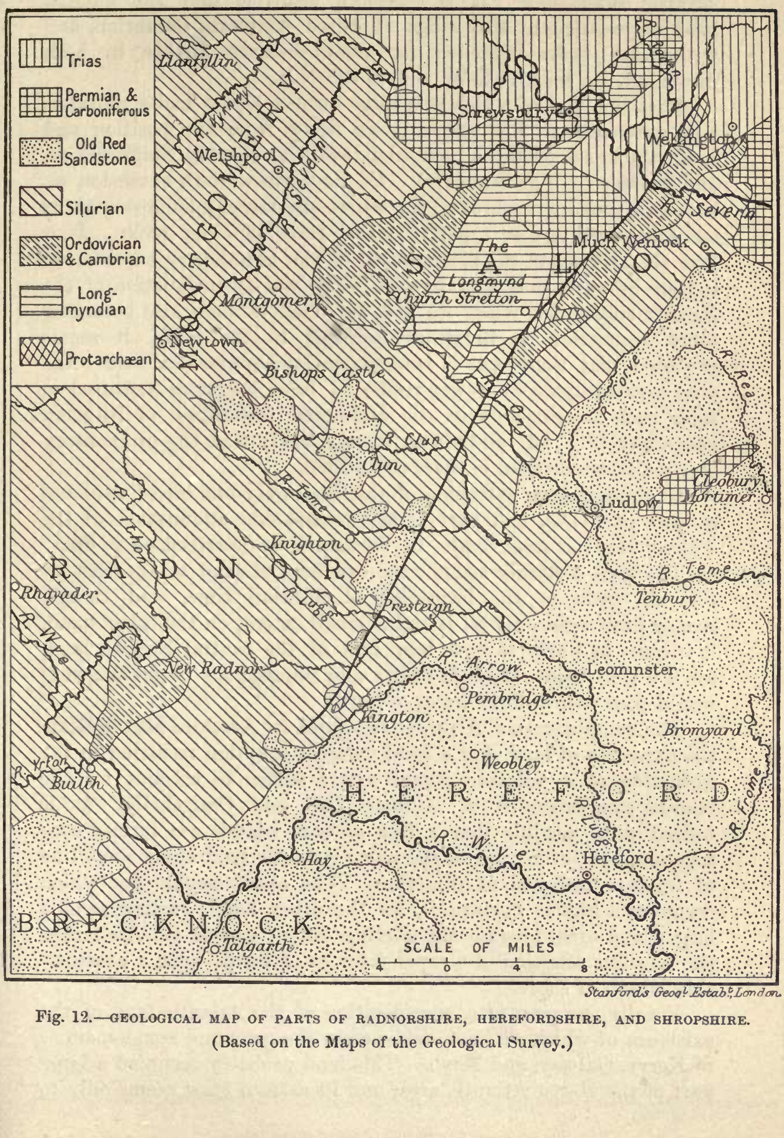


Fig. 12.—GEOLOGICAL MAP OF PARTS OF RADNORSHIRE, HEREFORDSHIRE, AND SHROPSHIRE.
(Based on the Maps of the Geological Survey.)

Shrewsbury) and near Wellington, surrounded by Permian and Triassic sandstones. It is therefore probable that the ancient land represented by this ridge of raised Archæan, Cambrian, and Ordovician rocks extended for some distance farther in both directions, *i.e.* both to S.W. and to the N.E.

That the land of which this ridge formed a part had a considerable extension to the eastward we know from the position and small thickness of the Upper Llandovery at Barr in Staffordshire, and Rubery in Worcestershire. Of its south-western extension we have evidence in Pembrokeshire, where the Lower Llandovery thins out southward against a partly buried ridge of older rocks. It is true that, owing to the concealment of the Llandovery outcrop, we cannot be sure that this western ridge was a continuation of the Radnor ridge; but when we find the Wenlock Beds also becoming more arenaceous as they are followed to the S.W., it seems probable that there was a continuous land-connection under the area now occupied by newer rocks. I have therefore ventured to show such a connection in the attempted restoration of Silurian geography (Fig. 13), and think it very likely that the promontory was really wider than is there delineated.

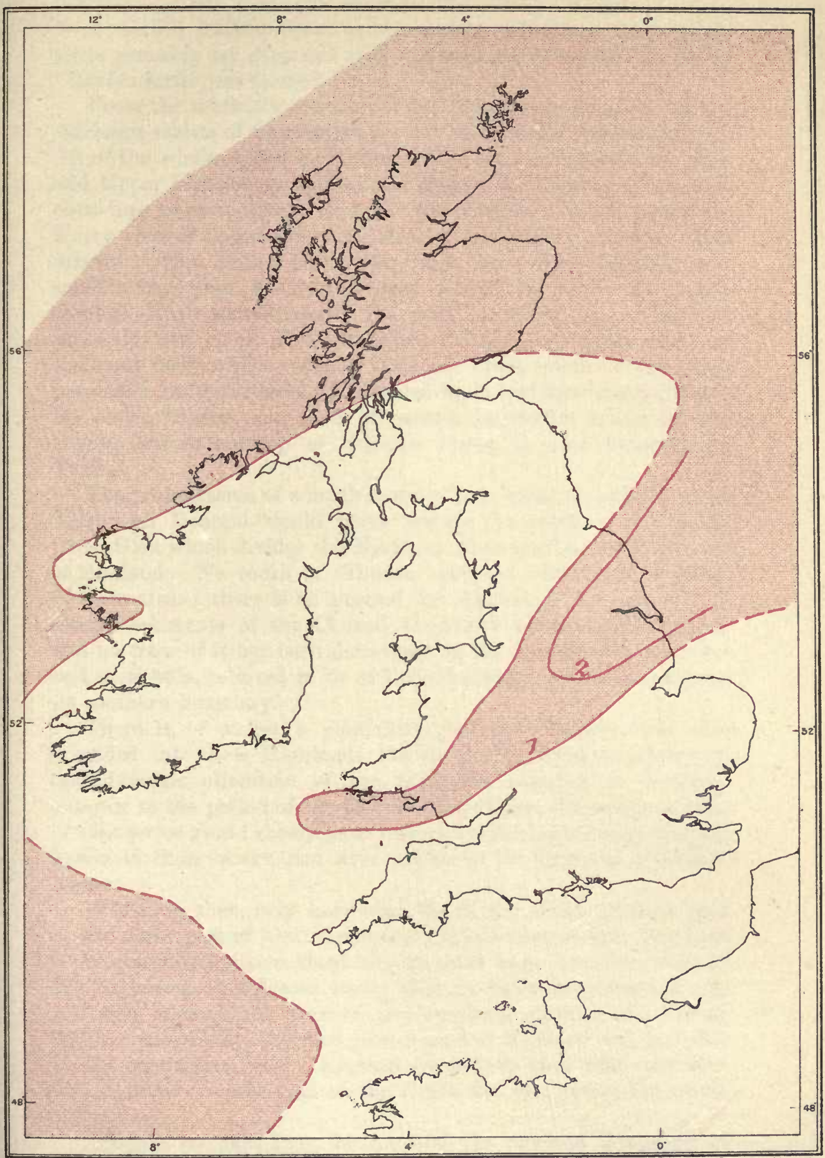
Of the northern extension of this land only one bit of evidence at present exists, and that is the remarkable attenuation of the Valentian series near Settle, in Yorkshire, as described on p. 89.

The facts certainly suggest the existence of land to the east or S.E. of Settle at the beginning of Silurian time, and though it may have been only an island of small extent, on the other hand, it is quite as likely to have been part of the central English land, for if a line drawn through Builth and Shrewsbury be prolonged it would pass within forty miles of Settle.

The conglomerates of the Girvan area in Ayrshire also indicate the existence of land, but a local volcanic eruption resulting in the formation of a volcanic island would suffice to account for the boulder-conglomerates of Mullock Hill and Craigskelly. It is indeed quite possible that a line of such islands was formed contemporaneously in front of the rising Atlantic land along some line of fracture initiated at this time. The quartz-pebble bed which occurs at a higher horizon is, on the other hand, suggestive of a larger land area, because the sorting out of quartz pebbles means the selective attrition of a rapid river or of waves upon a considerable length of shore.

Finally, we pass to a consideration of the Atlantic land of the existence of which we have evidence in the grits and conglomerates of Kerry, Galway, and Mayo. This land probably occupied a large part of the North Atlantic area, and its eastern coast seems only to

Fig. 13.—GEOGRAPHY OF SILURIAN TIME (LLANDOVERY).



London : Edward Stanford, 12, 13, & 14, Long Acre, W.C.

have reached Ireland at one or two points. Between these points there probably lay deep and wide bays, in one of which the Kerry Silurian series was formed.

From the southerly overstep of the Llandovery Beds on to the Archæan schists of Connemara we may infer that a considerable uplift of the whole region took place in the interval between the Bala and Upper Llandovery epochs, and that in the shaping of the new coast-line a promontory of land was formed which divided the Kerry area of deposition from that of the Killary and Clew Bay district. The Killary Silurians may have been formed in a smaller bay from which the coast curved eastward and passed through Mayo somewhere to the north of Clew Bay. Thence it probably ran in a N.E. direction through the great tract of Archæan rocks which occupies Donegal. How much of this tract may have been included in Silurian land, and how much (if any) lay under Silurian sea, it is at present impossible to say, for the nearest known outcrop of Silurian strata is near Pomeroy, in Tyrone.

The prolongation of a north-easterly line drawn through Western Mayo and Donegal would point toward the southern end of the Great Glen which divides the Northern from the Central Highlands of Scotland. No rocks of Silurian age have been found in either of these areas ; there is no ground for supposing that any of the altered sediments of the Central Highlands belong to this system, and no trace of it has been discovered in the narrow strip of slates and chert beds, believed to be of Ordovician age, which occurs along its southern boundary.

There is, of course, a possibility that the Silurian Beds once extended into these Highlands, but as the flexuring, compression, and dynamic alteration of the Highland complex is certainly anterior to the period of the Old Red Sandstone, the conglomerates of that series would surely have included stones containing Silurian fossils if those rocks had ever extended far into the Highland region.

Whatever, then, may have been the extent of the Atlantic land in the later part of Ordovician time, it is almost certain that both its extent and elevation above the sea must have been increased at the beginning of Silurian time; that its coast-line extended continuously through the western and northern parts of the British region ; and, lastly, that the greater part of Scotland was included in this continental land. Further, we believe that this continent also included a large part of the North Sea and nearly the whole of Norway.

Hitherto we have been dealing with the physical geography of the earlier or Valentian portion of Silurian time ; the later phases of the period now call for consideration.

The phase of the Wenlock Beds was certainly in the main one of subsidence and enlargement of the sea at the expense of the land. By this subsidence all the southern part of the central English land was carried deeper beneath the sea, and here we may pause to note that though the water in this part of the Silurian sea cannot have been really very deep, yet the deposits formed in it were limestones and calcareous shales. It is an instance of the fallacy of the idea that extensive beds of limestone were always formed in deep water and at some distance from land ; as explained in the introductory chapter of this volume, it is nearer the truth to say that limestones are indicative of clear water, whether formed near to or far away from land ; yet in the case of the Wenlock Beds we see that times when the water was clear enough for the formation of limestones alternated with times during which currents carried so much mud that nothing but shale or calcareous mudstone could be formed.

Much of this shaly material is barren of fossils, showing that the water was too continuously muddy for marine creatures to live in it ; while most of the limestones are crowded with fossils and are really made up of organic remains. It is indeed very probable that the accumulation of a foot of such limestone occupied as much time as the deposition of 6 feet of shale, and if this was the case, the time represented by the combined average thickness of the Woolhope and Wenlock limestones must have been as long as that represented by the much greater thickness of the intervening Wenlock shales.

From the recurrence of the calcareous Wenlock facies below Hertfordshire and its extension southward into Gloucestershire we may infer that the physical conditions which favoured its development were continuous across the whole Midland area, and that the depth of water gradually increased southward toward France, where there is evidence of the water having really been deep (see p. 11).

When, however, we pass in an opposite direction to the north-western side of the Midland area, we find a very different set of sediments ; thus in Denbigh the Wenlock series consists of shales with a band of felspathic grit, while in West Yorkshire and in Westmoreland it consists principally of flagstones and grits. Hitherto the source of all this arenaceous material has never been satisfactorily determined.

In the last edition of this book I quoted Sir A. Ramsay's suggestion that "part of the mountain of North Wales between

Conway and Cader Idris then formed land," and that it supplied some of this sandy material. It was, moreover, suggested that this land extended thence westward into Ireland, a view which then seemed possible, but which subsequent discoveries of Silurian fossils in the S.E. of Ireland make it impossible to maintain. It is now held that Silurian deposits must have originally extended eastward over Dublin, Wicklow, and Wexford, and were probably continuous with those of Wales.

This question of the derivation of the Wenlock grits must be considered in connection with that of the much thicker overlying series of flags, grits, and sandstones, for there can hardly be any doubt that all this arenaceous material, both of Wenlock and Ludlow age, was derived from the same source. We ought to find a clue to this source by ascertaining in what direction the arenaceous beds thicken. Now in North Wales the combined thickness of the Wenlock and Ludlow Beds, so far as the latter are complete, is about 5500 feet; in Westmoreland their equivalents to the top of the Bannisdale Beds are estimated to have a thickness of 13,000 feet; in Scotland the full thickness of the two series is not known, but excluding the series which is classed as Downtonian, and adding 1500 feet of Ludlow to 2200 feet of Wenlock (see p. 91), we get a combined thickness of 3700 feet, which is not even one-third of the amount in Westmoreland.

It seems therefore that, setting aside the highest Downton and Lanark passage beds, it is in Westmoreland that the combined Wenlock-Ludlow groups attain their greatest thickness, and are at the same time principally composed of arenaceous materials. It also appears that the total thickness decreases southward into Wales, westward into Ireland, and northward into Scotland; consequently we may infer that the material came from some eastern direction.

Land in this direction can hardly have been other than the continuation of the Builth and Longmynd ridge, the existence of which in Valentian time we have already had some reason to suspect. If such land continued to exist throughout the whole Silurian period, and if it furnished most of the arenaceous material which now forms such a thick pile of sediments in West Yorkshire, Westmoreland, and Denbighshire, it must have been of considerable extent, and must also have been a hilly land rising to great elevations above the sea-level. The line marked 2 in Fig. 13 indicates the possible position of the promontory during Wenlock time.

It is, however, possible that the height of the north-western side of the land was increased from time to time by spasmodic uplifts, while the sea-basin outside was gradually subsiding. There are indeed actual grounds for such a supposition in the phenomena of tilting and overlap near Builth, to which attention was called on p. 86. We may therefore infer that both the original and the subsequent uplifts were such as to give this land a general southerly or south-easterly slope, so that all the principal rivers ran in that direction, and having a gradual fall were not able to carry anything but mud into the southern sea. The N.E. coast, on the other hand, may have presented long bold lines of cliffs, backed by a range of hills, and broken only by the valleys of short and rapid rivers, which poured large quantities of sand into the north-western sea.

After the formation of the Aymestry limestone in the Salopian area, and of the corresponding zone of *Monograptus leintwardinensis* elsewhere, all subsidence seems to have ceased, and eventually an upward movement of the whole region supervened, which led to the emergence of fresh tracts of land and a corresponding narrowing of the seas. In the passage beds of Wales, Hereford, and Shropshire, and in the Lanarkian series of Scotland, we have evidence that the broad Silurian seas had been converted into shallow gulfs, in which only a peculiar fauna could exist. Graptolites have disappeared, few Mollusca are found, *Lingula cornea* is almost the only surviving Brachiopod, the principal tenants of these muddy and silty waters being the Eurypterid Crustacea and the primitive types of fish which are now classed as *Ostracodermi* (*Pteraspis*, *Cephalaspis*, etc.).

In these gulfs or bays the conditions must again have resembled those of the Bay of Fundy, for the tracks of unknown animals are preserved on the surfaces of some of the sandstones, showing that wide expanses of sandy mud were exposed and partially dried during the recession of the tides, which at the time of springs must have had a great rise and fall.

In Ireland a part of the Dingle Beds belongs to this transition period, and indicates the extensive erosion of the Atlantic land consequent upon its gradual upheaval and the eastward advance of its shore-lines.

CHAPTER VI

THE DEVONIAN PERIOD

THE Devonian system, with its variety of lithological facies and its complicated relationships to the rock-groups above and below, furnishes phenomena of great interest to the geologist, but at the same time presents stratigraphical and geographical problems which are very difficult to solve.

Although there is no longer any doubt about its existence as an independent system between the Silurian and the Carboniferous, there is still much uncertainty as to the correlation of the several members of the Upper Devonian series in Cornwall, N. Devon, South Wales, and Southern Ireland, and as to the most natural line of division between these beds and the Lower Carboniferous series.

The great feature of the Devonian system is what may be called its dual aspect, for both in Europe and in North America there are large areas where the normal marine facies is replaced by a great series of sandstones, flagstones, and conglomerates which are supposed to be of estuarine and lacustrine origin. The one facies is known as "the Devonian," and the other as the Old Red Sandstone, and though it is certain that the one is homotaxial with the other, they appear to occupy separate and distinct areas, except to a limited extent in the south of Ireland and in the N.W. of Russia.

Both facies occur in the British region ; the marine in Cornwall and Devon, the Old Red Sandstone in Wales and the Welsh "Marches," in Ireland and in Scotland. We can therefore begin with the most southerly area and consider first the typical marine Devonian with especial reference to the conditions under which its successive members were formed ; from Devon we can pass to South Wales and the other districts in which the Old Red Sandstone is found.

A. *Stratigraphical Evidence*

1. Cornwall and Devon.—The recent work of the Geological Survey in Cornwall has shown that the southern part of the county consists very largely of rocks which belong to the older Palæozoic systems, and that the boundary of the Lower Devonian crosses Cornwall along an east and west line running from Porth Towan on the west coast to the north of Truro and Tregony, whence it curves south-eastward to Veryan Bay. From this line northward to Boscastle and eastward to Plymouth and Torbay the country is occupied by Devonian rocks, the vertical succession of which, as established by Mr. Ussher, is as follows :—

Upper	*Entomis* shales Calcareous slates	Famennien and Frasnian.
Middle	Torquay and Plymouth limestones Slates and volcanic rocks	Eifelian.
Lower	Staddon grits Meadfoot Beds	Coblentzian and Taunusian.
	Dartmouth slates (Gedinnian).	

The lowest subdivision (Dartmouth slates) is a thick series of purple, red, and green slates with bands of hard grit or quartzite. It seems to be more than 2000 feet thick ; but the base of the series has not been seen, because it is not brought up in any of the anticlinal flexures, and because the whole group appears to be overlapped by higher beds southwards against a shore-line, so that it does not crop out along the boundary-line above mentioned.

The only definite marine fossil yet found in the Dartmouth slates is *Bellerophon trilobatus*, but Ussher describes that as fairly common though badly preserved ; and fish remains belonging to the genera *Pteraspis*, *Cephalaspis*, and *Parexus* also occur ; hence there is no reason for regarding the Dartmouth slates as other than a truly marine deposit. At the same time they must have been deposited in a land-locked sea or channel, the waters of which were in some way rendered uncongenial to the marine life of the period. It is probable that large rivers emptied themselves into this sea, and brought down so much iron in solution that few creatures except fish were able to live in the water. The frequent purple and red colouring of the slates is some confirmation of this view.

The Meadfoot group is a series of grey slates, grits, and quartzites, with thin lenticular limestones, containing numerous fossils, though these are generally in a bad state of preservation. Crinoids and Brachiopods are the most abundant. The higher beds near Looe include bands of fine red-specked grit, and pass up into the Staddon grits, which are hard, reddish, fine-grained sandstones and mudstones with few fossils.

The whole country around Plymouth, Dartmouth, and Torquay, where these rocks occur, has been so folded, plicated, and faulted that no reliable estimate of thickness of any of the subdivisions can be made, neither is it possible to indicate any definite horizons as lines of separation between the groups. It seems probable, however, that, even allowing for repetition by faulting and folding, the total thickness of the Lower Devonian series is between 3000 and 4000 feet.

It has already been stated that the Meadfoot Beds appear to overlap the Dartmouth slates southwards; they are believed to pass into the arenaceous Grampound and Probus Beds, which include beds of coarse grit and conglomerate, and are clearly littoral deposits formed near a sinking shore-line. From the component pebbles in these conglomerates we learn that not only were many derived from the adjacent Falmouth and Portscatho rocks, but that some came from an area of gneissic, schistose, and volcanic rocks.

Moreover, round Manaccan and Nare Head, south of the Helford river and on the border of the Lizard district, there is another tract of these conglomerates, which were formerly supposed to be of Ordovician age.

The Nare Head conglomerate consists of rock-fragments of various kinds and sizes, embedded in a felspathic and gritty matrix: some of the blocks are of large size, most of them are subangular, but a few are partially rolled and rounded. The stones consist of slates, quartzites, grits, and several kinds of igneous rock. Professor Bonney has examined a series of specimens obtained by Mr. Fox, and reported on them as follows: [1] "These rocks prove that at the epoch of their formation there existed at no great distance a district or districts in which the following rocks were well developed:—

"(*a*) Granitoid or gneissoid rocks, some of which at a period probably long anterior had undergone marked pressure modifications, which may very likely have produced a pseudo-stromatism, as in the North-West Highlands.

"(*b*) Fine-grained schists, some of which also indicate distinctly the effects of pressure subsequent to their assumption of a (rather minute) foliated structure.

[1] I am indebted to Mr. Fox for sending me Professor Bonney's unpublished MS., and to both of them for allowing me to quote from it.

"(*c*) True slates or argillites, in some cases certainly the former. Between *b* and *c* are many intermediate varieties.

"(*d*) Grits of various kinds, one almost a quartzite, some quartz-felspar grits, and others, apparently formed from a rock similar in character to *a* (*i.e.* containing quartz, felspar, and mica).

"(*e*) Several varieties of trachytic rock, some of which we may venture to call Andesite. From their abundance and variety it is probable that these fragments were derived from lava-flows rather than from intrusive masses.

"I have found no trace of any rock resembling either the Serpentine or Gabbro, or the basic dykes of the Lizard district, nor any fragments that exactly correspond with the gneisses and schists of that district. Some fragments bear a slight resemblance to rocks which occur in what I have called the 'Micaceous series,' but as the latter has been so modified by subsequent pressure these resemblances cannot be trusted."

Before passing northward into Devon we must glance at the Lower Devonian deposits of Brittany, which are quite as thick as those of Cornwall, being estimated by Professor Barrois to be about 4600 feet. They consist for the lower 3000 feet of dark green quartzites and hard gritty slates in alternating bands; these are succeeded by white sandstones (Grès de Gahard) and a group of fine grits and slates with lenticular beds of limestone (Grauwacke de Faou). It is evident that land cannot have been far off this area of deposition, and in all probability it lay to the north and west, occupying nearly all the space between Brittany and Cornwall.

Returning to South Devon we have next to consider the Middle Devonian series. This consists of dark grey slates succeeded in some places by thick masses of limestone, which, however, are discontinuous and seem to be replaced laterally by calcareous slates and volcanic rocks (contemporaneous lavas and tuffs).

The limestones have generally been described as coral-reefs, but without any proper consideration of the facts or sufficient examination of the component organic fragments. The supposition that they were such reefs seems indeed to be merely a perpetuation of the opinion formed by Sir H. de la Beche in the early days of geological knowledge,[1] and before the application of the microscope to the examination of rocks. The perpetuation of this view by more recent writers seems to be owing partly to a mistaken belief in the general distribution of corals throughout all parts of the limestone group, and partly to the fact that the limestone masses

[1] See *Report on the Geology of Devon and Cornwall*, 1839, p. 147, and *Mem. Geol. Survey*, vol. i. p. 92 (1846).

often form isolated hills or knolls which at first sight are suggestive of separate reefs.

Having paid much attention to the relative position and composition of the limestones around Torbay, I am confident that the reef theory is a mistake. The isolated position of the limestone-tracts is explicable by the manner in which the whole district is faulted and folded, so that the boundaries of the limestones are often faults or else flexures which bring the beds into a nearly vertical position. This can be seen from the diagrams in Mr. Ussher's Memoirs on the Torquay and Plymouth districts (explanatory of sheets 348 and 350 of the Survey Map).

Microscopical examination shows that the lower bedded limestones consist almost entirely of crinoid remains, and are really crinoid limestones. Some of the higher limestones are mainly composed of large massive Stromatoporoids (an extinct family of Hydrozoa), but others are ordinary shell-limestones in which detached and broken corals are common, but do not occur in such a manner as to suggest a coral-reef (see Introduction, p. 14).

The Upper Devonian consists of calcareous shales of different colours, purple, red, green, and grey, and it seems to be thicker in Cornwall than it is in South Devon. Vesicular basic lavas, tuffs, and breccias are often interstratified with the slates, so that volcanic eruptions seem to have been frequent during the later stages of the period. As the Carboniferous Beds on their southern border are unconformable to the Devonian, it is probable that much of the Upper Devonian is concealed beneath the overstep, and this will account for the more complete sequence which is found in North Devon.

Passing under the great syncline of Carboniferous strata which crosses the middle of Devonshire (see Fig. 14), the Devonian system emerges again in the north of the county, but there presents a very different aspect. The lowest beds are the Foreland sandstones, which consist of hard red sandstones with some coarse and even pebbly beds; they contain remains of *Pteraspis*, and there is little doubt that they are the equivalents of the Dartmouth slates. The overlying grey slates (Lynton Beds) are correlated by Mr. Ussher with the Meadfoot group, and the succeeding Hangman grits not only occupy the position of the Staddon grits but are lithologically similar to them.

The Middle Devonian is represented by the Ilfracombe Beds, a series of grey slates and flagstones with bands of earthy limestone. The Upper Devonian series appears to be thicker in North than in South Devon, and is divided into three groups: (1) the Pickwell Down sandstones; (2) the Baggy Beds (sandstones and

Fig. 14.—GEOLOGICAL MAP OF PARTS OF SOMERSET, DEVON, AND CORNWALL.

shales); (3) the Pilton Beds (grey slates or shales). The total thickness is uncertain, owing to flexures and faults, but may be as much as 3000 feet.

This incoming of thick sandstones and grits in the lower series of North Devon indicates an approach to land in a northerly direction, and it is clear that the sea in which the Devonian sediments were deposited had no great breadth from south to north, probably not more than 70 miles; for between the Quantock and Mendip Hills, a distance of only 16 miles, the whole of the Lower and Middle Devonian seems to have disappeared. This is inferred from the recent discovery of an inlier of Silurian rocks on the Mendips, which appears to be overlain unconformably by Upper Old Red Sandstone.[1]

Eastward, however, there is reason to believe that the Devonian sea extended continuously beneath the south of England, for rocks containing marine Upper Devonian fossils have been found in deep borings at Turnford, near Cheshunt, and at Meux's Brewery in London. Again, at Richmond, Kentish Town, and Crossness (in Kent) borings through the Cretaceous and Jurassic strata entered rocks of rèd, grey, and greenish colours, about the age of which opinion has differed, some referring them to the Trias, and others to Devonian or Carboniferous. I do not think they belong to the Trias, because the Triassic Sandstones generally maintain a uniform character over considerable areas, whereas the characters of the strata below London vary greatly; at Richmond they are soft variegated sandstones and marls, at Crossness hard quartz sandstones with red and grey shales, and at Kentish Town variously coloured sandstones and clays, with a thin bed of conglomerate. These variations might, of course, be due to the proximity of a shore-line; but, considering all the circumstances, and especially the high dip of the beds in the Richmond boring, I incline to the opinion of Professors Prestwich and Bonney, that these strata belong to the Old Red Sandstone or to the basal beds of the Carboniferous system, and not to the Trias.

In the Boulonnais Devonian slates and limestones actually come to the surface within a small area, and are known to extend eastward under parts of France and Belgium, till they emerge again in the Ardennes.

2. South Wales.—This area having also been recently revised by the Geological Survey, more complete information is now available, and it has been found that important stratigraphical changes take place when the beds are followed, either to the south-west or to the south-east, from the northern part of

[1] See *Quart. Journ. Geol. Soc.* vol. lxiii. p. 276.

the area. So long ago as 1872 Mr. W. S. Symonds had shown that the Old Red Sandstone of the Welsh borderlands could be divided into three sets or series of beds—a lower Red Marl or Cornstone series, a middle or Brownstone group, and an upper set of sandstones and conglomerates. These divisions have been adopted with slight modification by the Geological Survey, but the progress of revision has shown that while in the northern and eastern parts of the area there seems to be a conformable succession, in the west there is evidence of a break between the Cornstones and the Brownstones, the latter proving to be only a subordinate member of an Upper Old Red series, as tabulated below :—

Upper series	Red and yellow sandstones, quartz grits, and quartz pebble conglomerates.
	Brownstones. Red, brown, and purple sandstones, with occasional beds of shale, marl, and cornstone.
Lower or Cornstone series	Green and dull red sandstones with marls and cornstone conglomerates (Senni Beds).
	Red marls with bands of nodular limestones (cornstone) and irregular beds of red micaceous sandstones.

In Brecknock and the west of Carmarthen the Red Marl group is conformable to the marine passage beds of the Silurian described in Chapter V. (p. 86). Its thickness is difficult to estimate, but Mr. Cantrill considers that it may be as much as 4500 feet. The cornstones occur sometimes as continuous beds of pale red or green compact limestone, and sometimes as nodular concretions in the marls; they consist entirely of amorphous carbonate of lime enclosing some sand, and no fragments of organisms except obscure plant remains can be seen in them. They may owe their existence to the agency of some lime-secreting algæ, like that which forms the "sprudelstein" of Carlsbad (described by F. Cohn in 1862) and the travertine of the Mammoth Hot Springs in the Yellowstone Park, U.S.

The Cornstone series has yielded fish of the genera *Pteraspis* and *Cephalaspis*, and there can be no doubt that it is homotaxially the equivalent of the marine Lower Devonian and of the Lower Old Red Sandstone of Scotland. The Senni Beds are included in this series, because they also contain *Pteraspis*; they only occur in that part of the area which lies to the west of Brecknock, where they have a maximum thickness of 1200 feet.

The Brownstones overlie the Cornstone Beds in conformable succession, and no definite basement bed has been recognised by the Survey in Brecknock, though Mr. Symonds thought that there was a certain amount of discordance and overlap at their base. The Brownstones may have a thickness of about 2000 feet in the area around Brecknock, but thin both eastward and westward.

The uppermost group is generally marked off from the underlying beds by the incoming of a conglomerate composed of pebbles of vein-quartz, so rounded that the beds are said to look like shingle beaches. Above are grits, sandstones, and shales, which pass up into the Lower Carboniferous series. Its thickness seems nowhere to exceed 500 feet, but it has yielded a distinctive fish fauna (*Bothriolepis*, *Holyptychius*, etc.), and specimens of the bivalve known as *Archanodon Jukesi.*

When the formation is followed westward beyond Llandeilo several changes are found to take place. The base of the Cornstone series ceases to show an upward passage from the Tilestones, the basement beds becoming first sandy and then conglomeratic, at the same time gradually passing across the passage beds and the Ludlow mudstones till, near Carmarthen, they have overstepped the whole Silurian series and rest directly on the Bala Beds. The whole group also becomes thinner, and is not more than 2500 feet near Llandarog.

During the re-survey of the Gower district in the south-west corner of Glamorgan a most interesting and important discovery has been made, two small inlying tracts of Silurian (Ludlow Beds) having been found within the Old Red Sandstone area. Moreover, though the Cornstone series is present, it thins out within the area. Thus some 300 feet of Red Marls are seen below Rhossili Down, but they are not succeeded by Senni Beds, being overlain by Brownstones which pass up into red and white conglomerates, so that there is here an actual break between the two series. Moreover, on Cefn-y-Bryn the Red Marls are absent, the Brownstones are very thin (100 feet) resting on the Silurian, and are succeeded by some 300 feet of conglomerates, so that here the total thickness of Old Red Sandstone is reduced to 400 feet.

This extraordinary attenuation of the Old Red Sandstone, which has a thickness of 3000 to 4000 feet along its northern outcrop, suggests an approach to land in a southern direction, and furnishes an actual piece of evidence for the theoretical land-barrier which has been supposed to separate a Welsh lake from the Devonian sea on the south. The pebbles of the conglomerates were probably derived from this land ; they consist of rounded quartz-pebbles, subangular quartzites, and angular pieces of red jasper, some of which are silicified igneous rocks.

Passing to Pembrokeshire, the surveyors have found a normal succession by Langharne and Narberth, the lower series alone being about 2500 feet, and its basal beds containing bands of conglomerate and breccia, which are chiefly composed of pieces of felsitic rocks, vein quartz, and quartzites derived from the older Palæozoic and Pebidian rocks which lie to the north.

Along this northern outcrop the higher series is overlain unconformably by the basal Carboniferous strata, but in the south of Pembroke from Tenby westward there is a downward passage from the Carboniferous Limestone into the Upper Old Red, the lower part of which consists of quartzitic sandstones and breccias, below which is another group of red pebble-conglomerates, one being apparently conformable to the other, and the latter to the red marls below. It seems probable, however, that a break exists somewhere, and that there is also an overlap in the upper series northward.

Returning now to the central area, and tracing the changes that take place toward the E. and S.E., we find in the first place that where Silurian comes to the surface again near Usk there are no Tilestones or passage beds, but a sharp superposition of red grit on Ludlow mudstones. Consequently, we may infer that the conformity of the Red Marls to the Tilestones elsewhere is more apparent than real. Secondly, the Senni Beds are absent, and all the other groups are thinner; the Cornstone series is, however, less affected than the others, being still about 2800 feet by Abergavenny, Newport, and Cardiff. The upper series, however, diminishes to about 700 feet near Newport, about 500 of this belonging to the Brownstone group.

On the borders of the Severn and east of the Forest of Dean the Old Red Sandstone appears to be still of considerable thickness; but southward in the Mendip Hills it has diminished to a few hundred feet of the upper series, which rests on Silurian Beds.

3. Ireland.—*Southern Counties.*—The representatives of the Devonian system in Ireland have a special interest because some of them present points of resemblance both to the marine Devonian of Cornwall and Devon, and also to the Old Red Sandstone of Wales.

The structure of the south-western part of Ireland has been the subject of much discussion and difference of opinion. Even now the difficulties have been by no means cleared up, but the observations of Jukes, Du Noyer, Hull, and M'Henry have so far established the order of succession that some correlations can be made with a fair degree of certainty.

It was mentioned on p. 92 that the Ludlow Beds of the Dingle promontory were conformably succeeded by a great series of unfossiliferous slates and grits which have been called the Dingle Beds, and that the lowest part of this series is comparable with the Tilestones of Radnor and Brecknock. But the higher part contains conglomerates with pebbles of various older rocks, and included blocks of limestone with Silurian fossils, so that there must be a break somewhere below this conglomerate, just as there is really a break in the apparently continuous succession of the Tilestones and Old Red Sandstone.

It has generally been assumed that the Glengariff Beds, which occupy such large areas in Kerry and Cork, are the equivalents of the Dingle Beds; but Jukes was doubtful on the point, and M'Henry is of opinion that the correlation cannot be maintained.[1] Probably the mass of the Glengariff Beds is newer than the Dingle series, but it is also possible that the actual base of the former does occur in the Dingle promontory.

The Glengariff Beds consist in the lower part of hard green and purple grits with subordinate beds of slate, while in the higher part slates of red and purple tints predominate over the grits. No fossils have yet been found in them, though they are brought up along broad anticlinal flexures which range from the west coast of Kerry to the eastern parts of Cork. Their thickness has been roughly estimated at 8000 feet, but when due allowance comes to be made for folds and faults it may prove to be much less.

The Glengariff Beds have been compared with the Dartmouth slates, and so far as lithological characters go the resemblance seems to be great; but in view of the fact that much of the Upper Devonian of Cornwall consisted of purple, green, and variegated slates, which are very like the Dartmouth slates, there is at least a possibility that the Upper Glengariff slates are of Upper Devonian age.

In Kerry and Western Cork there seems to be a complete upward sequence from the unfossiliferous Glengariff grits through a set of red, purple, brown, and green beds, into the Coomhola Beds and the Carboniferous Slate. The Coomhola Beds are alternations of grey and brown grits with bands of dark grey slate, and they contain a marine fauna which correlates them with the Marwood Beds of Devon.

In the eastern part of Cork beds considered to be the Upper Glengariff slates are succeeded by sandstones and shales of yellow and green tints, followed by a few hundred feet of Carboniferous

[1] "The Geology of the Cork District," *Mem. Geol. Survey, Ireland*, 1905, p. 10.

shales which are overlain by the Carboniferous Limestone. The yellow sandstones are the equivalents of the Kiltorcan Beds and of the Upper Old Red ; they are believed to be of lacustrine origin, as they only contain what seem to be freshwater and terrestrial fossils, *i.e. Archanodon Jukesi* supposed to be an ancestor of the modern *Anodon*, fish of the genera *Bothriolepis*, *Asterolepis*, *Glyptolepis*, and *Coccosteus* with plants of several kinds, the ferns *Palæopteris* and *Sphenopteris*, and the Lepidodendroids *Cyclostigma* and *Knorria*.

For my present purpose it is unnecessary to discuss the correlation of this succession with that of North Devon ; but I shall assume that the Glengariff grits belong either to the Lower or Middle Devonian series, and that the other groups form a continuous upward succession comparable to that in North Devon.

It is of much more importance to note that in Ireland neither the Glengariff grits nor the higher purple and green slates extend northward of a line drawn from the mouth of the river Shannon to Tipperary, and thence to near the town of Kilkenny. The Kiltorcan Beds, on the other hand, not only extend westward to Killarney and the Dingle promontory, but they pass northward far beyond the Glengariff Beds, appearing in places from below the Carboniferous shale over a large part of Southern and Central Ireland.

In Cork and South Waterford the Kiltorcan group does not exceed a thickness of 500 feet, and has no conglomerate at its base, but northward it develops a thick basal conglomerate. The whole division becomes thicker to the N.W. till in parts of Tipperary and Limerick its conglomerates, sandstones, and shales have a total thickness of 3000 feet. Farther north, however, the beds seem to become thinner again.

Northern Counties.—In the north of Ireland there are three districts where rocks referable to the Lower Old Red series occur, but the deposits resemble those of Scotland and not the Glengariff Beds. The largest area extends from Lough Erne in Fermanagh to Pomeroy in Tyrone, a distance of about 30 miles, and the total thickness of the series is probably between 5000 and 6000 feet. It consists of dark red and chocolate-coloured conglomerates and sandstones with interbedded sheets of purplish andesite. The pebbles in the conglomerates are mainly derived from the contemporaneous andesites, but there are some of quartzite and schists from the Archæan area to the north-west.

These beds appear to have had originally a considerable extension to the north-west, for a small tract of similar materials is found in Donegal, near Mulroy Bay, having survived destruction in consequence of being let down by a fault into the mass of surrounding quartzites and schists.

The third tract is on the Antrim coast, north of Cushendall, and this forms a link between the Pomeroy area, 35 miles to the S.W., and the Caledonian Old Red of Kintyre, which lies 24 miles to the N.E. In Antrim the basal bed is a conglomerate consisting entirely of rounded quartzite pebbles and boulders up to a foot in diameter. Above is a thick series of red and brown sandstones with lenticular layers of shale, and still higher is a breccia of quartz-porphyry fragments derived from a mass of this material lying to the southward. The beds exposed measure several thousand feet.

From the facts above mentioned several inferences may be drawn. The well-rounded pebbles indicate long-continued attrition either on river-beds or by the waves on the shores of large lakes, or more probably by both agencies. The great thickness of pebbly and arenaceous material points to long-continued detrition of the surrounding country by subaerial agencies. The red colours show that all the iron which had been dissolved out of the older rocks was deposited in the form of peroxide, as it would be in lacustrine waters or on terrestrial surfaces.

4. Scotland.—The Old Red Sandstone of Scotland is everywhere unconformable to the older Palæozoic and Archæan rocks on which it rests, but the magnitude of the break varies in different parts of the region. It is least in Lanarkshire, where the highest Silurian red sandstones are succeeded by the true Old Red Sandstone without any apparent stratigraphical discordance, but elsewhere the break is much greater. Even in the Pentland Hills and in Ayrshire the break is so great that the Silurian and Ordovician rocks had been folded, upheaved, eroded, and planed down before the deposition of the Lower Old Red, which thus lies on their upturned basset surfaces.

Moreover, while no Silurian rocks have yet been found north of the Firths of Forth and Clyde, the Old Red Sandstone extends northward to the farthest point of Caithness and through the Orkney and Shetland Isles; its basal conglomerates resting with complete unconformity upon an irregular surface carved out of the flexured and faulted complex of Archæan rocks (see Fig. 15).

The Old Red Sandstone of Scotland has excited the admiration and kindled the enthusiasm of many Scotch geologists. Its immense thickness, the varied colours of its component strata, its peculiar scenery, and the extraordinary forms of its entombed fossils, have furnished themes for all who have studied this unique formation. Immortalised by the pen of Hugh Miller, the wonders of the Old

Red Sandstone are familiar to all, while its history in connection with the scenery of Scotland has been recorded in the graphic and artistic descriptions of Sir Archibald Geikie. Both writers have been struck by this massive thickness, and by the proofs of its having once extended far beyond its present limits over the gneissic and schistose districts.

Until recently much confusion and misapprehension prevailed with regard to the stratigraphical relations of the different parts of the Scottish Old Red Sandstone. Before the revision of the Southern Uplands by the Geological Survey the beds which are called "Downtonian" in the Official Memoir of 1899, and are classed as Silurian, were included in the Lower Old Red Sandstone; while the mass of the formation was often called the Middle Old Red. The latter, however, as developed on each side of the Central Lowlands, is now admitted by all to be the true Lower Old Red Sandstone, containing the *Pteraspis* fish-fauna which is characteristic of Lower Devonian time.

The deposits of the northern area contain a different fish-fauna, which has not yet been found in the southern area, and the term Middle Old Red is now applied to the beds which contain this second and newer fauna. Lastly, there is an Upper Old Red Sandstone which yields a third fish-fauna, corresponding with that same division in England, Wales, and Ireland (Kiltorcan Beds, etc.).

Some account of the characters, thicknesses, and relations of these several divisions in different parts of Scotland must now be put before the reader, in order that he may comprehend the facts which have to be explained before anything like a true history of one of the most important and interesting phases in the "building of the British Isles" can be written.

Southern Area.—This area must be considered to include not only the southern part of Scotland but the adjacent northern parts of England. The surface on which the Old Red Sandstones rest is so irregular that the local basement beds in different districts are probably of different ages, but they everywhere contain abundance of grauwacke pebbles and fragments of other rocks derived from the Silurian and Ordovician rocks of the Southern Uplands. This fact proves that when the period began a large area of these uplands formed dry land, which was subjected to the erosion and detrition of subaerial agencies. Whether this land was completely submerged before the end of this epoch so as to be covered by deposits of Lower Old Red Sandstone is uncertain, but these were certainly spread over a large part of it, and extended round its northern, eastern, and south-eastern borders.

The Lower Old Red of this region consists mainly of red and greenish sandstones and conglomerates, with thick sheets of andesitic lavas, the whole reaching a thickness of several thousand feet ; and yet it is evident that only a small portion of it remains, for it had been extensively denuded and partially destroyed before the Upper Old Red Sandstones were laid down upon it, so that the break between the lower and upper series in this region is very great.

The large tract of volcanic rocks which forms the Cheviot Hills is of Lower Old Red age, but the sandstones and conglomerates which flank the western sides of these hills belong to the upper division. The lower series may originally have extended continuously westward to and across the Lake District, but if so it has been destroyed during subsequent disturbances and erosions. It was probably a little later, *i.e.* in Middle Devonian time, that the older Palæozoic rocks of this district were forced up into their present positions, being folded, compressed, cleaved, and sheared by pressures acting from the south, as will be indicated in the sequel.

Even of the Upper Old Red there are only a few remnants left in Cumberland and Westmoreland, as at Mell Fell, Melmerby, and Roman Fell ; patches of conglomerate containing pebbles of various kinds, not only of local rocks, but of Silurian from the south of Scotland, of andesite and of gneissic and schistose rocks.

Midland Belt. — North of the Lowland area, and on the southern side of the Highlands, the Old Red Sandstone reappears from beneath the Carboniferous rocks and occupies a broad tract across the country from Arran and the Firth of Clyde to the coasts of Fife, Forfar, and Kincardine. The most complete succession of the beds composing the lower portion of the system is found in Forfar, where the sedimentary beds alone have a thickness of at least 14,000 feet, and intercalated in these are masses of andesitic lava, each composed of many flows and forming long ranges of hills.

For details regarding the stratigraphy of this Forfar series the reader is referred to an excellent paper by the late Mr. J. G. Goodchild,[1] and to a later one by Mr. G. Hickling.[2] At the base are 1500 feet of fine red sandstone and shale, succeeded by massive beds of conglomerate and coarse grit with a thickness of no less than 5000 feet, the pebbles being all of quartzite derived from the rocks of the Central Highlands.

The fossil fish obtained from this series are those of the Lower Old Red, but, according to Mr. Hickling, all of them have been obtained from beds in the middle of the series within a range of about 3000 feet, and none have yet been obtained from any of the

[1] *Geol. Mag.*, 1904, p. 600. [2] *Ibid.* 1908, p. 396.

higher beds so that there are at least 4500 feet which may have equivalents in the Orcadian series.

The Upper Old Red is best seen in Fifeshire, and its full thickness is estimated at 1000 feet. The patches of it which now occur are but the remnants of a very extensive deposit which must originally have spread over the whole of the Lowland area. The beds lie almost horizontally and with a complete unconformity on the lower series, so that there is a great break between, with proof that the lower series had been folded into a series of broad synclines and anticlines, and that in some places no less than 8000 feet of rock had been removed from the lower group before the deposition of the upper series.

The following brief description of the latter is quoted from Goodchild (*Geol. Mag.* 1904, p. 592): he says that where fully developed it consists of "(1) a basal conglomerate, which graduates upwards into (2) a variable series of red sandstones, often full of desert-sand grains (see ante, p. 8), and highly false-bedded in places, like an old desert sand-dune." These beds form a lower subdivision, and above them is a higher set of beds (3), in which the sandstones are not so deeply coloured. "This group (3) is generally characterised by the occurrence in it of some precipitated carbonate of lime. In some cases this compound occurs in the form of flakes which obviously represent broken-up sheets of chemically-formed carbonate of lime; in other cases the calcareous matter has segregated into a nodular form; while in some few instances the calcareous matter may occur as lenticular masses closely resembling some bedded limestones." They are, in fact, cornstones, like those found in the Old Red Sandstone of Wales.

The Midland belt of Old Red Sandstone is cut off by the great fault which brings up the metamorphic and gneissic rocks of the Central Highlands, only a few small tracts of the basal beds occurring on the north side of the fault-line, but these are sufficient to show that originally the lower series extended far northward into the region of these Highlands. This inference has been well expressed by Sir Archibald Geikie, who, referring to the hills that form the Braes of Doune, writes that "even from a distance the stratification of the conglomerates and sandstones of these uplands can be easily traced, the beds presenting their denuded truncated ends towards the mountains, to which they evidently at one time reached, and from the waste of which they were formed. If we prolong with the eye the lines of these truncated strata, we see that they probably once stretched far away into the interior of the Highlands."[1]

[1] *The Scenery of Scotland*, 3rd Edition, p. 160.

There is, moreover, another tract of Lower Old Red Sandstone around Oban in Lorne, where the lowest beds are conglomerates (from 15 to 300 feet thick), consisting almost entirely of pebbles and boulders of andesite, all well rounded, but some of them weighing as much as half a ton. "Considerable wave-action would seem to have been required to wear down these lava blocks into the shapes in which they lie in the conglomerates."[1] As the lavas of the Lorne plateau overlie these conglomerates, it is clear that the latter represent the broken-up remains of still earlier lava-flows. Further, as sandstone and purple shales are interbedded with the Lorne lavas, it is evident that the products of successive eruptions flowed into the area of deposition.

Northern Area.—When we pass north-eastward to Cromarty and Caithness we reach an area where even the detrital deposits are different, where there are no great contemporaneous lava-flows, and where no trace of the characteristic fauna of the Lower Old Red Sandstone has yet been found. Yet the total thickness of deposits in Caithness is even greater than in Forfar, being estimated at 17,000 feet.

The lowest beds are conglomerates and dark red sandstones, which have not yet yielded any fossils ; above are bituminous grey flagstones, which contain the peculiar fish-fauna now recognised as that of the Middle Old Red Sandstone and of the Middle Devonian of Russia. Some of the flagstones are so calcareous that they pass into bluish-grey earthy limestones, and some of the shales are so bituminous as to become impure oil-shales. "Throughout the whole series of strata, sun-cracks, rain-prints, and other surface-markings occur on most of the bedding-planes, whence the inference may be drawn that the original sediments were laid down on a sinking floor, and were subjected to repeated periodical desiccation."[2]

The lower beds of this series rise westward on a floor of the underlying schists, and outliers of the basal conglomerates and breccias cap some of the loftiest mountains in the Eastern Highlands, such as Morven in Caithness (2320 feet), Ben Griam in Sutherland (1936 feet), Meall a Grianam (2531 feet) in Ross, to the N.W. of Altruish Inn, and Mealfourfonie (2284) in Inverness. The conglomerates are probably not all of the same age, but are the shore deposits of successive horizons in the flagstone series ; nevertheless they show that some parts of the series spread far away to the westward over a denuded platform of the Moine schists and Hebridean gneiss.

[1] *Ann. Rep. Geol. Survey* for 1896, p. 55.
[2] *Sum. Prog. Geol. Survey* for 1900, p. 67.

Outliers of similar conglomerate are also found in Banff and Aberdeen. "The highest of them is that which runs up the valley of the river Avon above Tomintoul, where it reaches a height of upwards of 1300 feet above the sea. The coarseness of the conglomerate at this locality is remarkable ; huge blocks of the schists and other crystalline rocks of the district piled up in the conglomerate there, bear emphatic witness to the abrasion of the Highlands during, as well as before, the time of the Old Red Sandstone."[1]

The superposition of nearly horizontal Lower Old Red upon upturned Mesarchæan quartzites is shown in Fig. 15, which is taken by permission from a photograph belonging to the Geological Survey of Scotland. The patch of Old Red near Cullen is small, but a large tract nearly 20 miles long from north to south occurs to the east of Banff.

The Upper Old Red series is also found in patches throughout this Orcadian area, and it forms a continuous tract on the south side of the Moray Firth, by Nairn, Forres, and Elgin, where it passes southwards across the lower set of beds so as to rest directly on the Archæan schists.

B. *Building of the Devonian Continent*

From the facts and inferences stated in the preceding pages the reader will have realised that the transition from the Silurian to Devonian time was an epoch of great change, upheaval, and denudation ; further, that elevation, volcanic action, and mountain-building continued in progress during part of the Devonian period itself. In fact, the crust movements which took place at this time may be regarded as the first important stage in the building of the British Islands.

We have seen that no unquestionably marine deposits of Devonian age occur to the north of the Bristol Channel, nor in any part of Ireland. It is admitted that part of the great series of grits and slates at present known as the Glengariff Beds may be marine or estuarine deposits, in spite of the absence of marine fossils. Beyond the limits of these beds all the rest of Ireland seems to have been above sea-level during the whole of the period. Not only so, but it seems clear that the whole of the British region, except the south of England, formed part of a large continent which included the whole of Northern Europe, and extended westward over the greater part of the North Atlantic area.

[1] Geikie's *Scenery of Scotland*, 3rd Edition, p. 159.

C

B

A

Photo *H.M. Geol. Survey.*

Fig. 15.—VIEW NEAR CULLEN, BANFFSHIRE, SHOWING ARCHÆAN QUARTZITES (*A*), OVERLAIN UNCONFORMABLY BY OLD RED SANDSTONE (*B*) WITH GLACIAL DEPOSITS (*C*) ABOVE.

Let us now consider more closely the manner in which the British portion of this continent seems to have been built up, and let us begin with its southern border.

The stratigraphical relations and component materials of the Lower Old Red Sandstone in Pembroke and Carmarthen prove that land then existed to the north-west; and as the prevailing strike of the Welsh rocks is from S.W. to N.E., and as the primitive ridges carved out of these rocks strike in the same direction, and were clearly in existence before the deposition of the Carboniferous rocks, we may safely conclude that the compression and elevation which produced the flexuring, cleavage, and prevailing strike of the Welsh rocks took place at the beginning of Devonian time, and that the pressure of the crust movement came from the N.W.

Mr. Fearnsides has described the effects of the crust pressures on the rocks of Central and Northern Wales at some length in the volume recently published by the Geologists' Association.[1] The following are some extracts from his account. He points out that the effects of the pressures were most intense in the north-west of Wales, and gradually lessen toward the south-east. He considers that the Bangor-Llanberis ridges were driven in upon the Snowdon syncline, and that the great compression thus caused set up the cleavage which has converted the Cambrian and Ordovician shales of that district into such fine roofing slates. He writes: "The peculiarity of this district is the wonderful uniformity and verticality of its cleavage, which peculiarity, in the opinion of the present author, is due to the rigidity and resistance to compression offered by the overlying mass of the Snowdonian volcanic series. Beneath the Snowdon syncline the cleavage of the lower slates maintains its character and general direction, but, flowing as it were around the hard intrusive masses which occur, it is sometimes seriously modified and the slates are spoiled for quarrying." In the Lleyn peninsula the cleavage is much less developed, although it is parallel to the Llanberis district; this has been explained by Professor Harker as due to the deeper burial of the buttress-ridge of Pebidian volcanic rocks.

Mr. Fearnsides believes that the Harlech pericline (see Fig. 7) lies in a large triangular area which is bounded by great thrust faults. One on the north runs from near Criccieth by Tremadoc and Llanfrothen to Festiniog: "it generally separates Tremadoc and older beds from the Ordovician and introduces into the succession a gap which has long been interpreted as an unconformity whose peculiarities have not been explained. Upon the Moelwyn

[1] "Geology in the Field," Part IV., *Geology of North and Central Wales*, p. 814.

it fans out into a number of minor thrusts, which, with many similar ones among the shales and arenig-volcanic rocks about Festiniog have induced the magnificent, gently-inclined shear or flow cleavage which makes the slates there so valuable."

To the south-east of the Harlech area there is the well-known Bala fault, with its branch through Dolgelly to Barmouth. "The hade of this fault is almost vertical, with some slight overturning to the north," and Mr Fearnsides believes that it is really an overthrust. He also remarks that "within the main fault triangle, the rocks subjacent to the thrusts have usually taken on a strike not very different from that of the thrust-planes, and are themselves frequently traversed by minor thrusts which have been induced by the overdrag"; though the mass of the Harlech grits has resisted these pressures.

"Southwards from the Bala fault, the normal N.E. and S.W. strike is resumed, and in the broad syncline of the Central Uplands continues with but minor undulations round the grit masses. . . . Within this syncline the intenser compressional effects of the Caledonian-Devonian pressures were waning, and . . . have expended themselves rather in the development of minor folding than in the production of a widespread cleavage. . . . With a more accurate survey the map should appear like the modern maps of the physically similar uplands of South Scotland."

Passing now over to Ireland we find a similar tract of Cambrian, Ordovician, and Silurian rocks, displaying similar features and occupying a similar position with regard to the Old Red Sandstone. This Irish area, however, presents us with an additional feature of much interest in the immense mass of granite which has invaded the Ordovician rocks, and seems to have consolidated under a continuous cover of these rocks, which must consequently have been lifted up by it into an elevated dome. The exposed portion of this granite is more than 60 miles in length, with an average breadth of 11 or 12 miles, and as the Upper Old Red Beds pass on to its surface in places, it must not only have been intruded, but also denuded and exposed before the close of the Devonian period.

Moreover, recent researches have established a connection between the granite and the felsitic lavas which form intrusive sills and dykes in the adjacent Ordovician rocks; and also between certain post-Ordovician porphyrites and bostonites occurring in County Waterford and similar intrusive rocks in Pembrokeshire.[1] From these resemblances it is concluded that all these intrusions took place during the Lower Devonian period.

[1] Compare papers by Kilroe and M'Henry in *Quart. Journ. Geol. Soc.* vol. lvii. p. 488; by Cowper Reed, *Ibid.* vol. lvi. p. 690, and *Ibid.* vol. lxi. p. 603.

It appears, therefore, that the crust movements were associated with vulcanicity, and that in the Cambro-Hibernian area they led to the introduction from below of at least one great magma of igneous material, the main mass of this forming a laccolite which solidified into granite ; while portions of it were injected into the fissures of the surrounding rocks and crystallised into several kinds of felstone.

Moreover, when we consider the similarity of the rocks on each side of St. George's Channel, the close correspondence in the strike of the flexures, and the similar cleavage phenomena of the two districts, it becomes almost certain that at this time they were united to form one continuous tract of land. This land might well receive the name of St. George's Land, and it might be regarded as a Greater Wales, the present Wales being only a severed and worn-down portion of it.

Let us now consider the manner in which the more northern ranges of mountains were formed, and the probable physical features of the region in which the great northern deposits of Old Red Sandstone were accumulated.

From the distribution of these deposits, as described on p. 114, we gather that the principal physical features of Scotland had been developed between the close of Ordovician time and the opening of the Devonian period ; that is to say, that the three principal hill-ranges were already in existence, and were separated by two intervening valley troughs, though it is probable that both these, and especially the southern Lowland trough, have been widened and deepened since Devonian time.

It was stated that the Lower Old Red may have extended over the greater part of the Southern Uplands and certainly spread all round it, and that it must also have stretched northward far into the interior of the Central Highlands ; but it is probable that this maximum extension was not attained till quite the later part of the epoch, when the highest part of the lower series was being deposited (Auchmithie conglomerate, etc.).

In the northern area a higher series, the Middle Old Red, comes in, and its basal beds rise westward to great heights on the gneissic area of the Northern Highlands. This area was doubtless a sloping surface, and the great thickness of 17,000 feet was only reached along the bottom of the intermontane depression, which was a north-easterly prolongation of the Great Glen.

We thus gain a general impression that the altitude of the land increased toward the north and north-west, each tract of high ground rising to a greater elevation in that direction, so that the central range was higher than the southern, and the N.W. range higher than the central. Let us now inquire whether this inference is confirmed by their tectonic structure.

It will be convenient to begin with the southern range, because its inclusion of the Silurian rocks clearly determines the date of its uplift, compression, and denudation. The following statements are condensed from the description given in the Survey Memoir:[1] "The tectonic centre of the tableland does not lie midway between its present north and south limits, nor does it coincide with the existing watershed of the region, but rather with the trend of the Northern Belt" (see p. 72). The tectonic axis appears, in fact, to have coincided roughly with a line drawn from Loch Ryan through the granite of Spango Water to the valley of the North Esk, its north-eastern end being buried under newer rocks.

In the Southern Belt the axial planes of the isoclines generally dip toward the S.E., while parts of the Central Belt exhibit the structure of a synclinorium, the isoclines on its northern side dipping to the N.W. and forming the southern flank of the

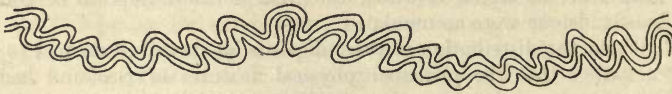


Fig. 16.—DIAGRAM OF FAN STRUCTURE AND ISOCLINAL FOLDS.

compound anticlinorium of the central axis. This axis, where typically developed near Abington and Leadhills in Lanark, presents the structure of a pinched-up fan, the central or primary fold forming an arch with nearly vertical sides, and the flanking isoclinal folds dipping towards it on each side, in the manner shown in Fig. 16.

The phenomena of the Southern Uplands are therefore simply those of greatly compressed and crumpled areas, and could have been produced by pressures acting almost equally from both sides, *i.e.* from N.W. and from S.E. Cleavage and schistosity have only been developed to a small extent, and are confined to certain districts, the rocks as a rule not being cleaved.

The structural features of the Central Highlands have not yet been fully described, but certain facts have been made known. The plication of the rocks is even more intense than in the southern area, and the strata are thrown into a series of complicated compound flexures on a large scale. There does not seem to be any definite central axis, but only a repetition of plicated fan-shaped folds and overfolds. The isoclines are sometimes inclined to the S.E. and sometimes to the N.W., and in at least one case a periclinal or dome-

[1] "The Silurian Rocks of Britain," *Mem. Geol. Survey*, 1899, vol. i. p. 70.

shaped structure has been observed. There are many faults, but they seem to be either of the normal or simple reverted faults, and no great thrust-planes have yet been recorded.

The reconstructive effects of lateral pressure are much more strongly developed than in the southern area. All the rocks are more or less schistose, and though most of them were probably schists and gneisses of Mesarchæan age, before they were subjected to the post-Silurian pressures, yet the secondary foliation produced by the latter can often be distinguished from the primary foliation. The pressure metamorphism also varies in intensity, being much greater in some districts than in others, this being probably the explanation of what has been described as "progressive metamorphism."

Nothing newer than Ordovician has been found in the area, and that only in a narrow strip along the southern border, while the N.W. side is occupied by Archæan schists of the Moine type, so that not only the greatest crushing force but also the greatest vertical uplift seems to have been on that side.

We now come to the northern area, which was the scene of much more violent displacements. Brief reference to the intense plication, faulting, and thrust-movements in the North-West Highlands has been made in Chapter II, but a fuller account of these phenomena should now be given, and the following is adapted from that published in the Memoir on the North-West Highlands.[1] The principal results of the compressing forces are there stated to be :—

1. The rocks have everywhere been thrown into a series of folds which are bent over toward the W.N.W., so that they are isoclines with a dip to the E.S.E.

2. In many places the cohesion of the rocks has given way so that the continuity of the strata is broken by reverted faults and thrust-planes, the latter being divisible into major and minor thrusts (see Fig. 17).

3. By the major thrusts the following effects have been produced : (*a*) portions of the Cambrian strata have been heaped up and driven westward over the underlying rock-masses ; (*b*) huge slices of Hebridean gneiss, with sometimes covering tracts of Torridonian and Cambrian rock, have been driven over the displaced Cambrian masses ; lastly (*c*) portions of the eastern schists have been forced nearly horizontally over the other masses so far to the westward that in some places they have passed over all of them, and rest on the undisturbed Cambrian outcrop (see Fig. 18).

4. The more powerful displacements caused differential movements in the component materials of the rocks, which resulted in the development of new schistose structures, and in some places

[1] *Mem. Geol. Survey*, 1907, p. 463 *et seq.*

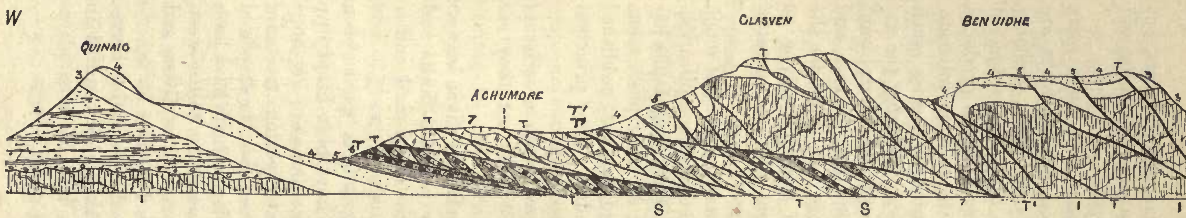


Fig. 17.—SECTION FROM QUINAIG, ABOVE LOCH ASSYNT, TO GLASVEN AND BEN UIDHE.

(Distance about 6 miles.)

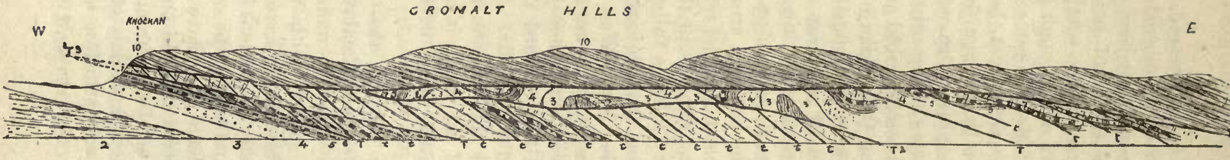


Fig. 18.—SECTION FROM THE KNOCHAN CLIFF, NEAR ELPHIN, THROUGH THE CRONALT HILLS.

(Distance about 6 miles.)

Cambrian:
- 7. Durness Limestone.
- 6. Serpulite Grit.
- 5. Fucoid Beds.
- 4. Upper quartzite.
- 3. Lower quartzite.

S. Bands compounded of Durness Limestone, Serpulite Grit, and Fucoid Beds, repeated by minor thrusts.

t & T. Thrust-planes.

T^1, T^3. Major thrust-planes.

2. Torridon sandstone.
1. Hebridean gneiss.
10. In Fig. 18, Overthrust tract of the Eastern schists lying on the plane of the Moine thrust (T^3).

These figures are reproduced from the Report on the Geology of the North-West Highlands in *Quart. Journ. Geol. Soc.*, by permission of the Council and the Authors.

the crushing and shearing has been so great that bands of rock have been entirely broken up and reconstructed (*i.e.* mylonised).

From these statements it is evident that the crumpling up of the north-west area, and the piling up of such huge masses of material on one another (a literal piling of Pelion on Ossa), must have produced a mountain range of great magnitude. Judging from the intensity of the effects produced on the rocks as compared with those seen in the Alps, where such a repetition of thrusts seldom if ever occurs, the Caledonian range must have been much grander and loftier than the Alps.

If the above descriptions of the tectonic structure of the three mountain districts of Scotland are compared with one another, it will be seen that they show a progressive increase in the amount of compression, metamorphism, and displacement; all these effects of lateral pressure being greatest in the north-west and least in the south. It is customary to say that the pressure exerted on the Scottish region came from the S.E., but we must remember that in Norway similar displacements indicate an equally powerful force acting from N.W. to S.E. Again, we have seen that the structure of the Southern Uplands suggests equal compression from both directions, and that of North Wales pressure from the N.W. only.

Consequently it seems probable that the forces which produced these extraordinary displacements both in Scotland and in Norway were developed from a median axis outward in both directions, which were those of least resistance. Simple contraction of the earth's crust at a time when it was thinner than now, and under conditions which localised the compressive effects, would perhaps account for the phenomena.

The comparison of the three Scottish areas raises another point, which is of much geographical importance, and that is the question whether the three ranges were raised contemporaneously or successively. The date of the Southern uplift is fixed, but, for aught we know, the uplift of the Northern and Central Highlands may have begun at an earlier epoch. It is indeed certain that the flexuring and faulting of the Northern Highland blocks antedates the thrust-plane movements, and there may have been a considerable interval of time between the two epochs of movement, during which the pressures gradually developed force enough for the production of the great displacements.

If indeed the theory of equal compressional forces acting from both sides against an axial resistant mass be a correct explanation of the facts, it is probable that the outer ranges would be ridged up first in the form of simple flexured anticlinoria. Continuance of the pressures would then raise and compress the central axis, and further continuance would develop such outward pressures as to produce thrust-planes in the outer ranges. Thus the first uplift of the outer ranges may have taken place in Silurian time ; the date of the central axis we know, and the final intense development of the pressures in the outer ranges may have occurred either at the same time or even during the actual formation of the lowest Old Red Sandstones.

It is therefore probable, from the physical and tectonic point of view, that the north of Scotland was eventually raised to a much greater elevation than the southern part of the country. We may suppose that in the early part of Devonian time the Scottish region formed part of a large continent which was traversed by a series of parallel mountain ranges, probably five, of which the outer were the highest ; the arrangement being similar to the ranges of western North America at the present day, where the coastal Cascade and Nevada ranges on the one side and the Rocky Mountains on the other enclose ranges and plateaus of lesser height between them.

The North-West Highlands are an isolated remnant of the worn-down core of a range that may have rivalled the Alps and the Sierra Nevada in height. In the Central Highlands we have part of a more irregular range or series of mountain massifs, perhaps a combination of ridges and domes. The south of Scotland was evidently a tract of no great elevation above the surrounding country, and may have been merely an elevated plateau. If then this was a central plateau, where were the more southern ranges?

It will be remembered that we found an area of high elevation and intense pressure acting from the N.W. in North Wales and producing the usual S.W. to N.E. strike. If this line were prolonged it would meet the great range of the Norwegian fells, and it would pass over that very part of Yorkshire where Ordovician and Silurian rocks underlie Carboniferous Limestone, and where we saw reason to believe that an uplift took place in Silurian time (see p. 96). This then may be a broken, sunken, and buried portion of the outer eastern range of the Caledonian mountain system. Inside this one of the minor flanking ridges seems to have crossed what is now the Pennine Range and the Lake District (see p. 115).

Now if the relative heights of the mountain ranges of Scotland increased from S.E. to N.W., so in all probability would the relative levels of the intermontane valleys or depressions. Consequently the Midland trough would be a lowland and, possibly, not very far above the sea-level, so that it soon passed into the condition of a lake, while the floor of the Great Glen was still an intermontane river-valley.

Finally, after the completion of the mountain building and during the period of great volcanic outbursts which followed it is possible that some local and differential subsidences took place, leading to the production of downthrow faults and rift-valleys. Mr. C. T. Clough informs me that the fault along the Great Glen, and that of the main boundary fault, as well as some of the other subparallel faults, are later than the folds in the adjoining schists, and they are also in the main later than the time of the Lower Old Red. It is possible, therefore, that these faults were initiated about the beginning of the Middle Old Red time, though of course there have been many subsequent movements along them. Such faulting and subsidence along the northern continuation of the Great Glen may have led to the formation of the great basin in which the northern or Middle Old Red deposits were accumulated ; to this point we shall recur in the sequel.

C. *Geography and Geographical Changes*

The picture of the Devonian continent which I have endeavoured to portray in the preceding pages is of course a theoretical one, and may have to be modified by future discoveries ; but before we can hope to understand the physical conditions under which such remarkable and unique formations as the three series of "Old Red Sandstones" were accumulated, it is absolutely necessary to form some idea of the processes which established those conditions. It will be seen from what follows that the theoretical conclusions, to which I have been led by a consideration of the facts, does furnish a more or less satisfactory means of explaining the problems of the Old Red Sandstone.

I will now indicate the general geographical conditions which seem to have prevailed during the formation of the Lower Devonian and Lower Old Red, for these may certainly be regarded as practically contemporaneous deposits.

From the facts connected with the Lower Devonian of Brittany and of Southern England and Cornwall, it was inferred that a considerable area of land then lay between the two areas and included at first all the southern part of Cornwall. This land was probably an uplifted extension of that which we have suspected to exist to the west of Brittany throughout the Ordovician and Silurian periods. Moreover, from the repeated alternations of arenaceous and argillaceous sediments we may infer that it was a mountainous land from which many rapid streams and rivers carried large quantities of detritus into the surrounding seas. After this initial elevation, however, it is evident that subsidence took place, the consequent erosion and recession of the coast-line being marked by the position of the Grampound and Manaccan conglomerates.

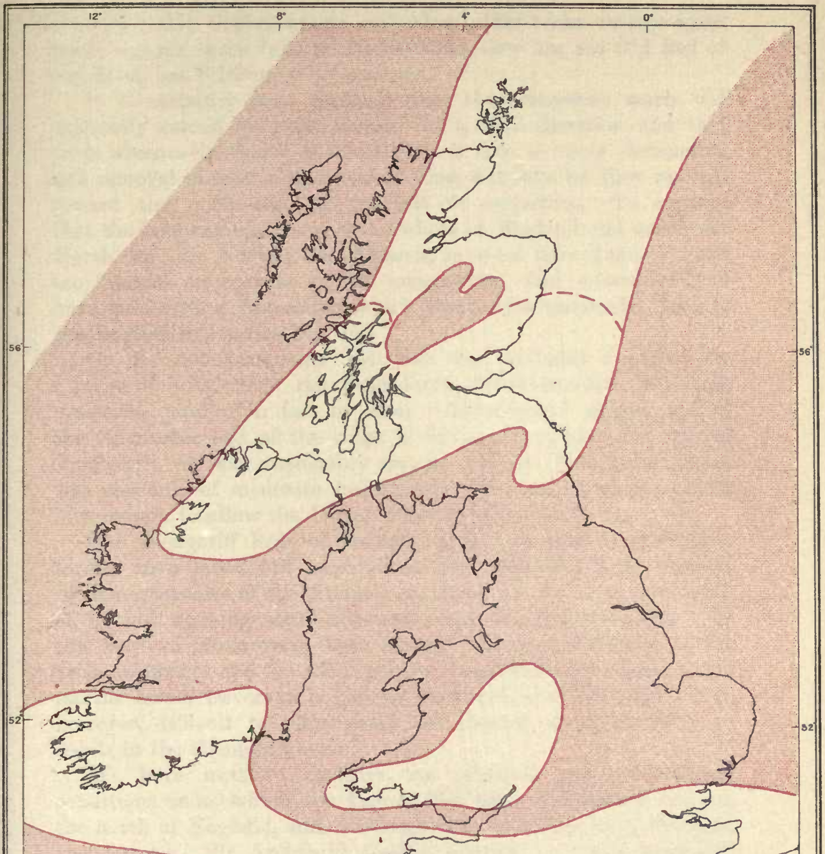
The northern shore of the Lower Devonian sea seems to have run from the Bristol Channel on the west to a little north of Cheshunt in Essex on the east, whence it curved south-east to Lille, Mons, and Namur. It is indeed possible that in Lower Devonian time the sea did not reach so far north as London, for at present we have no proof that any of the red rocks which occur under the London basin are older than the Upper Devonian.

We next come to the question of the conditions under which the Cornstone series of Wales was formed. For a certain length of time during the transition from the Silurian to the Devonian period the area was doubtless an estuary; but the red marls and nodular limestones of the Cornstone series are not ordinary estuarine deposits, and are more probably of lagunic or lacustrine origin. The great thickness of this series of beds is remarkable, for if the area of deposition was a freshwater lake it must have been a very deep basin. Again, if it was a lake the land barrier between it and the Devonian sea must have been very narrow, for the distance between the Cornstone outcrop near Cowbridge and the north coast of Devon, where the beds are marine, is only 17 miles.

It was in fact the narrowness of this space, and the absence of any actual evidence for such intervening land, which prevented me from adopting the theory of such a barrier in previous editions of this work; but the recent discoveries in Gower, considered in connection with the absence of Cornstone marls in the Tortworth and Mendip districts, certainly favour the view that a narrow but hilly tract of land extended westward from Somerset along the space now occupied by the Bristol Channel. Moreover, if the area to the north of this ridge was a lake basin, the land must have been continued westward till it joined on to that which I have called St. George's Land round the S.W. corner of Wales.

Another point for consideration is the probable distance to which the Cornstone series, and consequently the lacustrine area, may have extended in northerly and north-easterly directions. These beds must certainly have covered Radnorshire and have reached to the borders of Montgomery if not farther, just as they still extend through South Shropshire to and beyond Bridgenorth, though the series is appreciably thinner in the Clee Hill district. On the eastern side, however, the formation passes under the

Fig. 19.—GEOGRAPHY OF LOWER DEVONIAN TIME.



London: Edward Stanford, 12, 13, & 14, Long Acre, W.C.

unconformable Coal-measures, and when older rocks emerge again from beneath these beds in Staffordshire they are not Old Red of any kind, but Silurian and Cambrian.

It is certainly most probable that the Cornstone marls did originally extend to some distance in a N.E. direction, and that their absence in South Staffordshire is due to their destruction and removal in later Carboniferous time, but how far they reached toward the north-east we are left to conjecture. To suppose that the lake extended across the whole of England and across the North Sea into Norway and Sweden, as some have done, is quite too fanciful an exercise of the imagination, and consequently I have preferred a restoration which limits this particular lake to the English region (see Fig. 19).

On its south-east side the lake was probably bounded by a range of hills which ran from South Gloucestershire in a N.E. direction, parallel in fact to other "Caledonian" ridges, and as the Gloucester end of the ridge is flanked by Upper Old Red at Tortworth, we may reasonably assume that its N.E. continuation was also only of moderate height, and that most parts of it were low enough to allow the Upper series to pass over them.

The Glengariff Beds of Ireland we may suppose to have been formed in a broad but land-locked bay, enclosed almost entirely by the extensions of the Atlantic continent to the north and south of it, but opening south-eastwards into the Devonian sea. In this way we can account both for the immense thickness of the Irish sediments and for their general resemblance to those of the marine Lower Devonian in Devon, Cornwall, and Brittany. It is, however, difficult to understand the absence or great rarity of fossils in the Glengariff grits.

We have next to consider the physical and geographical conditions under which the Lower Old Red of Northern Ireland, the north of England, and the south and central parts of Scotland was formed. Sir Archibald Geikie, writing in 1879, expressed the opinion that these deposits must have been formed in three separate freshwater inland lakes, for which he proposed the names of Lake Cheviot, Lake Caledonia, and Lake Lorne.[1] Moreover, he rejected Murchison's view that the Caithness flags were of later date, which was based on the fact of the very different fish-fauna, and endeavoured to explain this difference on the supposition that the Orcadian area is that of a fourth lake which, though contemporaneous, was tenanted by a different assemblage of fish.

To this theory, however, many objections have been raised. In the last edition of this book I provisionally accepted it, chiefly

[1] *Trans. Roy. Soc. Edin.* vol. xxviii. (1879).

because it was a subject to which Sir A. Geikie had devoted much attention, and because I was then unable to suggest any better explanation. At the same time I pointed out that "from the proofs which have been adduced of the original wide extension of the Old Red Sandstone, it might be thought that the three principal basins could hardly have been separate lakes, but must have been inlets proceeding from one large inland sea, the greater part of which lay to the east of Scotland."

Since then the theory of separate contemporaneous lakes has been combated by Messrs. Macnair and Reid,[1] and by Mr. G. Hickling.[2] By the first two authors great stress is laid on the stratigraphical difficulties which present themselves on the assumption that the deposits of the Caledonian and Orcadian areas were of practically the same age. They were disposed to regard the whole succession of deposits from the Downtonian of Lanark to the top of the Caithness Beds as a marine series formed on successive platforms during the subsidence of the whole region beneath the sea. This theory, however, ignores some important facts, and creates as many difficulties as it explains.

Messrs. Macnair and Reid were certainly on the right track when they pointed out that some of the fish-genera found in the Caithness flagstones occur also in the Middle Devonian of Russia and North America. Since they wrote, Dr. Traquair has shown that the fish-fauna of Caithness is undoubtedly newer than that of Forfar, and much nearer in its general affinities to that of the Upper Old Red. Dr. Smith Woodward informs me that though the Russian fossils are very fragmentary, he thinks they justify the statement that the Orcadian fauna does occur in the Russian marine Middle Devonian.

Mr. Hickling also feels the difficulties with regard to the physical evidence, pointing out that the outlier of Towie in Aberdeen is only 25 miles from the faulted border of the Caledonian area, and that it occupies such a position on the flank of the Grampian ridge that, if the relative levels of the country have not been greatly changed, the two series of deposits must have been continuous. He also argues that though the Caithness flagstones are newer than the fossiliferous beds in Forfar, there is a great thickness of beds below them, which may be of Lower Old Red age, and again that there is some 5000 feet of beds in the Caledonian area which overlie the fossiliferous zone, and may be equivalent to part of the Caithness series.

There is much force in these arguments, but there is one

[1] *Geol. Mag.*, 1896, pp. 107 and 217.
[2] *Ibid.* 1908, p. 396.

weak point in them, for it is an assumption to suppose that the relative levels on the northern and southern sides of the Grampian range have not been changed since the time of the Old Red Sandstones. It is quite possible, and even probable, as I have shown on p. 126, that the area within which the Orcadian series was accumulated had originally been elevated to a higher level than the Caledonian, and that the lowest beds in the Orcadian area are not older than the Auchmithie conglomerate, the base of which is about 3000 feet below the denuded summit of the Forfar series, and about 11,000 feet from the base of that series.

It must be admitted that the occurrence of Lower Old Red in Lorne makes it very probable that difference of level was not sufficient to exclude that series entirely from the Orcadian area. Hence the most reasonable view, when all the facts are taken into consideration, is that all the areas of deposition eventually communicated with one another, but that it was only during the later part of the Caledonian stage that deposition began in the Orcadian area. There may have been at that time some differential sinking in of the intermontane tracts, increasing the relative depth of the Orcadian basin, and at the same time it seems to have become stocked with fish which could not have reached it by any southern route.

With regard to Lake Caledonia, I see no reason for imagining that the Lorne and Cheviot areas were not parts of it. On the contrary, it is only natural to suppose that the Caledonian sandstones of the Pentland Hills were originally continuous with those of Berwickshire, if not directly across the intervening space, at any rate round the eastern end of the Uplands. In the Cheviot area there was little deposition of detritus, for it became the focus of intense volcanic action, whereby a thickness of some 1500 feet of andesitic lavas were piled up. This area was probably at the southern and shallow end of a bay which opened northward into the deeper part of Lake Caledonia.

In the same way there is no reason why the lake-waters should not eventually have passed round the western side of the Grampians into Lorne. From the Scottish side of the North Channel they swept across into Ireland, and must have covered a large area in the north of that country, including the whole of Antrim, Derry, Tyrone, and Fermanagh, with parts of Donegal and Sligo.

This view of the geography of Lower Devonian time is represented on Fig. 19, the restricted area in the Scottish portion of the map showing the probable limitation of the Caledonian lake in the early part of the period, while the more extended area indicates the tracts which were covered by water toward the end of this stage and in Middle Devonian time.

The epoch of the Middle Devonian did not bring very much change in the geographical conditions of the southern portion of our region. If the Brownstone series of the Welsh borderland belongs to this part of the system, there is nothing to show that the physical conditions were very different. It has the aspect of a lacustrine formation, but the prevalence of sandstones, which in Carmarthen are often pebbly, suggests that the velocity of the streams running into the lake was rather greater than during the formation of the Red Marl series. Moreover, on the west it has a more limited extension than the latter. These facts may be interpreted as indicative of a further slight uplift of the area, raising it higher above the sea and lessening the size of the lake.

No representative of the Middle Devonian has been found in Ireland, and this again points to renewed upheaval. At the same time there is no indication that the sea over Devonshire became shallower, only that the water became clearer, which might well be due to alterations in the courses of the rivers.

In Europe to the eastward, however, there is distinct evidence of subsidence at this time; the Middle Devonian sea extended farther north over Germany and Russia than that of the Lower Devonian did, reaching into the Baltic provinces and thence by St. Petersburg to the White Sea and Novaya Zembla. Moreover, this Russian sea was probably continuous, across the Polar area, with the sea which covered the greater part of North America.

No Middle Devonian has yet been recognised in Norway nor in Greenland, but on the Sognefiord and Dalsfiord there are red sandstones which have been referred to the lower division, but, as they contain no fossils, it is just as likely that they belong to the Orcadian series. Moreover, sandstones with fish of Upper Old Red age have recently been found on the east coast of Greenland, so that it is by no means unlikely that there was an inlet or gulf extending from the Polar Devonian sea south-westward between Greenland and Norway.

We are now in a position to offer an explanation of the Orcadian fish-fauna. It is that in Middle Devonian time there was an unequal tilting movement of the continental region, its south-west portion (Ireland and Wales) being raised while its northern and eastern parts were depressed. This would lead to some alterations in the drainage system, and whereas the outlet of the Caledonian lake had previously been a river flowing across the centre of Ireland into the southern sea, the subsidence in the north-east may have caused an outlet to be established from the Orcadian basin into the Polar Sea, and by this outlet the fish of Middle Devonian seas would obtain access to the Orcadian basin.

It remains only to consider the changes which led to the formation of the highest portion of the Old Red Sandstone system. These changes were probably both tectonic and climatic; there were certainly crust movements during the interval, but these seem to have been greater in Scotland than in England or Ireland, and the final movement was clearly subsidence of the whole region, leading naturally to a modification of the climate.

In the Anglo-Welsh area the wider extent of the Upper Old Red, and the gradual upward transition from it to the marine Carboniferous strata, are facts which make it nearly certain that the area was undergoing subsidence, and that it was being gradually brought down to the level of the sea. The pebble-conglomerates are probably shingle-banks and beaches, the pebbles having been obtained partly from the erosion of the pebbly portions of the western Brownstones, and partly from the upper reaches of river-valleys which were now drowned beneath the advancing waters.

The area may for a time have been a freshwater lake, but there is no positive proof of this, for though the *Archanodon* is doubtless an ancestor of the modern freshwater *Anodon*, yet its own ancestors were probably marine molluscs, and the theory of its freshwater habitat is much weakened by the fact of its occurrence in the Tuedian Beds of Northumberland, which also contain stunted marine shells. It may have preferred brackish water to fresh, or was capable of living in either.

In Ireland there was a similar subsidence, so that a large part of that country was converted into a lacustrine area; probably a large lake, which was eventually invaded by the sea. On the most recent geological map of Ireland[1] tracts of Upper Old Red are coloured as cropping out from beneath the Carboniferous Beds as far north as Newport in Mayo and a tract on the southern border of Sligo. Southward its occasional emergence in the form of inliers proves it to underlie Eastern Galway, Roscommon, Longford, Westmeath, and King's County, and thence through the south of Ireland.

It is doubtful, however, whether we should be justified in concluding that the whole of this large area was ever a freshwater lake. It seems more likely that in the beginning small saline lakes were formed in the lowest depressions, and that it was only

[1] This forms part of a Geological Map of the British Islands, on a scale of 25 miles to an inch, issued by the Geological Survey in 1906. Price 2s.

as the climate became more humid that a larger freshwater lake covered the central part of the area and had an outlet into the sea. Finally, the sea may have crept up this outlet and have converted the area into a brackish lake or a series of lagoons. Thus the highest beds of the series, which are part of the marginal beds, may have been formed after the invasion of the sea. There can be little doubt that this was the actual course of events; the only question is whether the sea made its way into the basin before the epoch of the Carboniferous shale.

Finally, we pass to the North British areas of deposit. The great break at the top of the Caledonian Old Red, and the fact that its beds had been broadly flexured before the deposition of the Upper Old Red, prove that the whole Scottish and Borderland area had in the interval again been subjected to disturbance and crust pressure. The unconformity of the Upper to the Middle Old Red shows that the chief disturbance and uplift happened in the interval between those stages.

There is good reason to think that the climatal conditions of the Old Red Sandstone continent were throughout of a more or less arid type, so that large parts of it were sandy and rocky deserts like those of Central Asia at the present day. The Caithness flagstones may indicate a partial and local change to more normal pluvial conditions, as Goodchild suggested in 1898;[1] but if so the succeeding unconformity marks a return to desert conditions, during the prevalence of which the lake dried up and disappeared, and the whole region became an arid and rocky waste, subject to the erosive and destructive effects of high winds, a hot sun, and occasional torrential rains.

There seems to have been a continuance of such conditions during the formation of the lower part of the Upper Old Red, for, as Goodchild has pointed out, "the presence of grains of desert-sand on many platforms, the prevalent bright red colour of the rock, the strong false-bedding, suggestive of desert-sand dunes, the angular character of much of the material forming the conglomerates, and their large size and tumultuous mode of accumulation, the constant occurrence of casts of desiccation cracks and the frequency of rain-pitted surfaces, all combine . . . to indicate that it was formed under continental conditions and during the prevalence of an arid climate."[2]

The contrast between the lower and upper portions of the Upper Old Red has been mentioned on p. 116, and was regarded by Goodchild as indicating a return of more humid conditions,

[1] *Trans. Geol. Soc. Glasgow*, vol. xi. p. 101.
[2] *Proc. Geol. Assoc.* vol. xviii. p. 119 (1904).

when subsidence had carried the land very nearly down to the sea-level, and when the rainfall, if not more copious, was at any rate more regular and more evenly distributed.

Under these more genial conditions vegetation again sprang up, and larger more permanent sheets of water were formed. By these lakes the saline deposits of older desiccated lakes would be absorbed, and much similar material would be carried down in solution by the streams which ran into them. "Amongst the substances thus accumulated may safely be counted solutions of sulphate of lime. These, when brought into contact with decomposing organic matter, underwent certain chemical changes, one of which resulted in the precipitation of the lime in the form of the carbonate. Thus, it seems probable, thin sheets of chemically-formed carbonate of lime were formed in the shallows—evaporation, of course, also taking a part in the process; and then also, as it appears to me, nodular masses of calcareous matter were formed in the sediments that were in process of deposition" (*op. cit.* p. 120).

Goodchild therefore considered the Cornstone Beds in the Upper Old Red of Scotland to be evidence of a climate and surface-conditions that were transitional between those of the preceding dry period and the moist semi-tropical climate of the succeeding Carboniferous period. In conclusion it should be noted that, with the re-establishment of permanent lakes, fish from the Upper Devonian sea made their way into the region, and thus the third fish-fauna of the Old Red Sandstone finds a natural explanation.

CHAPTER VII

THE CARBONIFEROUS PERIOD

THE history of the Carboniferous period is a great contrast to that of the Devonian. The latter is mainly concerned with the building up of a great continent with lofty mountain ranges, immense volcanoes, broad valleys, and large lakes or inland seas. The Carboniferous period witnessed the slow subsidence of this continent, the submergence of its outer and lower parts, and the gradual detrition of its mountain ranges, some of which were soon reduced to the condition of islands. Finally, as the subsidence decreased or became intermittent, we have a record of the spreading out of detritus in shallow seas to form the vast swamps in which our Coal-measures were deposited.

In the British region the Carboniferous system is usually divided into two great stages or series, a Lower and an Upper, and as both include several thousand feet of strata and must each represent a considerable length of time, it will be convenient to deal with them separately. I shall commence therefore with considering the geographical conditions under which the Lower Carboniferous series was formed.

A. *Lower Carboniferous Time*

Rocks of Lower Carboniferous age cover large portions of the British Islands, and exhibit much variety in respect of lithological composition. If, however, we disregard minor variations, three principal types or facies may be distinguished, namely—

1. A southern or shaly facies.
2. A central or limestone facies.
3. A northern or mixed facies.

All three of these facies occur in England and in Ireland, but in Scotland only the northern type is found. Different subdivisions of the series have been made in different districts, and these have not yet been accurately correlated with one another, but the following table will show the main divisions in roughly parallel order :—

SOUTHERN.	MIDLAND.	NORTHERN.	
Shaly Facies.	Limestone Facies.	N. England.	Scotland.
Carboniferous Slate (Ireland). Fremington and Pilton Beds, ? 3000 to 4000 feet.	Upper limestones (Dibunophyllum zone), 900 to 2000 feet.	Upper Bernician sandstones and shales, 800 feet.	Upper limestone and Edge Coal Beds, 1200 feet.
	Middle limestones (Seminula zone), 800 to 1200 feet.	Middle Bernician limestones and shales, 2000 feet.	Lower limestone, 600 feet.
	Lower limestones (Syringothyris and Zaphrentis zones), 1200 to 1800 feet.	Lower Bernician (a varied series), 1700 feet.	Oil shale group, 3000 feet.
	Lower shales (Cleistopora zone).	Tweedian group (Fell sandstone and Cement-stone Beds), 2000 feet.	Calciferous sandstone group, 4600 feet.

It is unnecessary to describe these deposits with the view of eliciting facts indicative of shore-lines, as we have had to do in the case of pre-Carboniferous periods, because we know that we have to deal with the subsidence of the Devonian land, and we may assume that all the lakes and lowlands of that land sank beneath the Carboniferous sea. Our task, therefore, is to ascertain what parts remained as islands or promontories above the level of that sea, and to what distance the main coast-line was carried back from the position it occupied in Devonian times.

1. Central Area.—For several reasons it will be convenient to begin our examination with the limestone facies ; both because the limestones are the most conspicuous and best known members of the series, and because we shall find evidence that a large tract of land extended across the central part of the British region during the earlier part of the period. I propose, therefore, to take the existence of this land as a theorem, and to marshal the facts in such order as seems best calculated to support the truth of the statement.

For this purpose we must start with the Bristol area, which has become the type of the limestone facies in consequence of Dr. A. Vaughan's work on the zonal succession of the limestones in that and the neighbouring districts.

The chief zones which Dr. Vaughan has established in the Carboniferous Limestone of the Bristol and Mendip areas are—

5. Dibunophyllum zone		Upper division.
4. Seminula ,,		
3. Syringothyris ,,		Lower division.
2. Zaphrentis ,,		
1. Cleistopora ,,		

In the Mendip Hills this series of beds has a thickness of about 3000 feet. Near Bristol it is only 2250, owing to the diminished thickness of the *Zaphrentis* and *Syringothyris* zones. Near Chepstow it is reduced to about 1500 feet, and near Micheldean to 600 feet. All the zones appear to participate in this thinning out, but there is, moreover, a replacement of the limestones of the *Dibunophyllum* zone, first by shales and finally by shales and grits, till near Micheldean the highest limestone belongs to the *Seminula* zone, and is overlain by gritty sandstone which has naturally been regarded as "Millstone Grit."

About 37 miles north of this are the Clee Hills in south Shropshire, where Carboniferous Limestone is again found, but only in the form of a thin band between Upper Old Red Sandstone and the grits which underlie the Coal-measures. In this band Dr. Vaughan has identified representatives of the two lower zones, each only a few feet thick; above these are about 30 feet of clays, shales, and thin limestones, which may represent one or more of the higher zones, and above them are grits about 250 feet in thickness. Consequently it seems probable, as Dr. Vaughan remarks, "that the entrance of the grit-facies was even earlier in the Clee Hills area than in the Micheldean district."

The only other explanation of the facts would be that there had been some erosion of the limestone series before the deposition of the grits. However this may be, it seems clear that on the Titterstone Clee we are very close to a shore-line against which the Carboniferous Limestone was thinning out. As a matter of fact, on the Brown Clee to the north there is no limestone, and only 50 feet of grit intervenes between Old Red Sandstone and Coal-measures.

From the facts of the case we seem justified in concluding that the area in which the Upper Old Red had been deposited subsided much more rapidly in the south than on its northern side, so that its floor was tilted southwards and became a slope on which the Carboniferous Limestones were formed. We may also infer that it was only within what had been the limits of this lake that representatives of the lower zones of limestone extended so far to the north. West of the lake, where higher ground existed, we might expect the lower zones to thin out against a steeper shore-line and along a more southern line of latitude.

This seems actually to have been the case, as will be seen from the following *résumé* of recent researches in South Wales from the annual Summaries of Progress of the Geological Survey.

Along the southern side of the South Wales coalfield the Carboniferous Limestone, though seldom more than 1000 feet thick, seems to include representatives of all the zones. Along the northern side, however, its thickness is much less, varying from 500 to only 100 feet, and this attenuation appears to be mainly due to the disappearance of the lower parts of the limestone, *i.e.* the *Zaphrentis* and *Syringothyris* zones.

Near Kidwelly, on the east side of Carmarthen Bay, where the northern outcrop comes into the cliffs, the absence of these zones has been proved; the *Cleistopora* shales are present, but are directly overlain by the *Seminula* zone, and the total thickness of the limestones is only 600 feet.

At Tenby, in Pembrokeshire, on the south side of the Coal-basin, the sequence of zones is complete, and the total thickness about 1200 feet; but at Pendine, on the north, and opposite to Kidwelly, though all the zones are represented there is a break in the middle of the series, the lower part of the *Zaphrentis* zone being overlain by a conglomerate of rolled limestone pebbles, succeeded by limestones of the *Seminula* zone.

A little farther north-west there is again a total absence of the *Syringothyris* and *Zaphrentis* zones, and finally the *Cleistopora* zone thins out or is overlapped by the *Seminula* zone about three miles west of Templeton. The ultimate representative of the Limestone series is a band of the *Seminula* zone, which rests on Lower Old Red Sandstone and is surmounted by Millstone Grit, the latter lying on its eroded surface, so that here (near Haverfordwest) its final disappearance is caused partly by the thinning out of zones, and partly by erosion when Millstone Grit was formed. It is, at any rate, fairly certain that even at the close of Lower Carboniferous time the great subsidence had not carried the coast-line much to the northward of Haverfordwest.

Passing now across St. George's Channel to Ireland we find Carboniferous rocks resting on Cambrian around Wexford Harbour, and running in a strip south-westward to Ballyteige Bay. The zonal age of these beds is not yet known, but they probably belong to the higher part of the Limestone series. South of Wexford, according to Kinahan, they consist mainly of limestone, but northward they are largely replaced by red shales, sandstones, and conglomerates. Farther west, at the mouth of Waterford Harbour, the limestones are underlain by grey shales and Upper Old Red; consequently it seems probable that the Wexford area was not submerged till the later part of the epoch, and that it then formed a bay which shallowed toward the north-east.

North of Waterford the Ordovician area is bordered by Old Red Sandstone to and beyond Thomastown, but N.E. of this place it rapidly thins against what was evidently a steep slope of Ordovician and granite. Near Goresbridge yellow sandstones cross the river Barrow and lie on the Carlow granite, while a few miles farther north they and the overlying shales disappear, being overlapped by the lowermost limestones, which rest directly on the granite near Bagenalstown. How far this overlapping by higher and higher beds may go on in the country to the northward is not known, but it is believed that some part of the Lower Limestone group borders the Granite and the Ordovician tract as far north as Naas, in Kildare; beyond that it appears to be overlapped by the Calp shales and the higher limestone, which strike eastward to the coast of Dublin Bay (see map of Ireland, Fig. 22).

The relations of the Carboniferous rocks in County Dublin have been described in detail by Jukes,[1] who showed that they must have been deposited in a bay or inlet during the progress of a steady subsidence of the whole area, the result being that the Lower Limestone was overlapped by the Upper Limestone, and the latter by the beds which were formerly called Coal-measures, but are really the equivalent of the Pendleside series described by Dr. Wheelton Hind.

The basal beds of red sandstone and conglomerate are only found in the central axis of the area, in the Portraine and Donabate district, and above them are shales succeeded by limestones which probably belong to the lower division. Both northward and southward, however, these lower beds are overlapped by dark grey earthy shales and dark limestones which rest directly on the granite to the south of Dublin, and frequently enclose fragments and blocks of the granite. On the northern border of the area, between Rush and Skerries, the limestone includes beds of flagstone and conglomerate containing pebbles derived from the Ordovician rocks, and Dr. C. A. Matley has recently shown that these beds belong to the *Syringothyris* zone, a continuous succession from the Upper *Zaphrentis* zone to the top of the *Dibunophyllum* zone being there exposed. Near Naul to the westward there is a quarry in which the rock seen is partly limestone and partly a mass of cemented boulders consisting of blocks of Ordovician slate, grit, and greenstone bound together by the calcareous material of the limestone. Of this breccia Jukes observes: "This is evidently

[1] *Mem. Geol. Surv. Ireland.* Explanation of Sheets 102 and 112, p. 22 *et seq.* (1875), and *Geology of Dublin*, by G. W. Lamplugh and others (1903).

a portion of the very beach or margin of the Carboniferous sea in which the fallen blocks and shingle from the wasting land above were enveloped in the calcareous deposits of the Carboniferous period" (*op. cit.* p. 65).

The facts described in the Memoirs above quoted seem explicable only on the supposition that the beds were deposited in a bay which had land to the south, east, and west of it. The hill of Howth, on the north side of Dublin Bay, seems at one time to have been a peninsula or promontory projecting from the eastern land, and finally an island in the Carboniferous bay.

North of the area just described and around the town of Drogheda is another tract of Lower Carboniferous strata lying in a hollow between ridges of Ordovician rocks. The Lower Limestone is only found in the western part of this area, and disappears about two miles east of Slane, owing "to the conformable overlap of the higher beds of the formation on to the Silurian [*i.e.* Ordovician] rocks, over which they were deposited along a gradually shelving shore."[1] This tract seems, therefore, to occupy the site of another bay narrowing and shallowing eastward.

The isolated tract of Carboniferous rocks which runs northward from Kells and Ardee to and beyond Carrickmacross includes a nearly complete succession of the Limestone series, and proves that these beds must have originally extended all over the Ordovician tracts of Louth, Cavan, and Monaghan. With respect to the counties of Armagh and Down it has been questioned whether their higher parts, consisting of granite which has been thrust up through the Ordovician rocks, were ever completely covered by the Carboniferous sea ; but the granite of the Carlingford and Mourne Mountains is not of pre-Carboniferous date, like that of Wicklow, but is post-Carboniferous, and almost certainly of Eocene age. Consequently these mountains did not exist in Carboniferous time, and the Carboniferous Limestone may have extended over them. There is, in fact, good evidence that it did, for not only does a tract of such limestone border the southern side of the Carlingford Mountains, but patches of it altered to a saccharine marble occur on them to a height of 1000 feet.

The larger tract of granite to the northward is much older, and is believed to be of pre-Carboniferous age, but its western end has been largely invaded and raised by the intrusion of granitic and basic igneous masses in Eocene time, so that the present elevation of all this central part of Down may be due to uplift at this late period. At any rate there can be little doubt that the sea of the Carboniferous Limestone passed completely over the county

[1] *Mem. Geol. Surv. Ireland.* Explanation of Sheets 91 and 92, p. 35.

of Armagh from Dundalk and Carlingford to Armagh town and Lough Neagh. With respect to the eastern part of County Down, sandstones, shales, and limestones belonging to the lower division of the series occur at the northern end of Strangford Lough; they rest on Ordovician rocks and dip to the N.E. at an angle which, if prolonged to the S.W., would carry them a long way in that direction. Consequently there is no good reason for thinking that any part of Down remained above the level of the Carboniferous sea.

From the facts above mentioned it seems clear that the Irish portion of this central land was indented by two bays or inlets, one of them covering the S.W. corner of Wexford, and another the eastern part of County Dublin; also that beyond the latter land projected westward in the form of a promontory, and reached as far north as Drogheda and Clogher Head, but that the whole of County Down was submerged at an early date in the Carboniferous subsidence.

It seems, therefore, that the coast of the land which we have been following must have bent eastward across the Irish Sea, and that we must seek its continuation in North Wales or in Northern England. There is Carboniferous Limestone in Anglesey and along the northern coasts of Wales, but Messrs. Hind and Stobbs have recently proved that the lowest limestones of North Wales, Flint, and Denbigh correspond with the upper part of the *Seminula* zone of the Bristol succession. It follows that no part of this area was submerged until the beginning of the Upper or Viséan stage of the Lower Carboniferous series.

In Derbyshire and South Lancashire again nothing older than the *Dibunophyllum* zone has yet been found, but at Ingleton, near Settle, in Yorkshire, the basement beds of the Carboniferous system are certainly as old as the *Seminula* zone, and may belong to the underlying *Syringothyris* zone. Here, therefore, we seem to be on the very border of the sea which followed the first or Tournasian stage of the Carboniferous subsidence; and we infer that the whole of North Wales and of the Pennine area as far north as Settle had remained in the condition of dry land throughout this earlier part of the period.

These inferences are confirmed by what is known of the zonal succession of limestones in North Lancashire and Westmoreland. It has not yet been fully worked out, but Professor Garwood has collected fossils which lead him to believe that the lowest limestones near Kendal, Shap, and Ravenstonedale are referable to the *Syringothyris* zone, and that the underlying shales with the basement conglomerate may belong to the *Zaphrentis* zone.

Farther north, however, there seems to have been a low ridge which remained unsubmerged till a later date, for the lower sandstones and limestones of Ash Fell and Roman Fell are believed to thin out towards Cross Fell. The existence of a ridge running across Cumberland and Westmoreland was indicated by the late Mr. J. G. Goodchild, who had surveyed a large part of those areas and had studied the Carboniferous rocks of the neighbouring districts. He believed that [1] this ridge formed an island at the time when the conglomerates and sandstones of Roman Fell were being deposited, but that it was rapidly submerged and entirely covered by the sea before the epoch of the Upper (Yoredale) Limestones. The position of the ridge can be determined by drawing a line round the points where the Lower Carboniferous Beds are thinnest. Thus the beds below the Yoredale series, along the Pennine range, are found to be thinnest in Teesdale (400 feet) and near Milburn, where they are 700 feet; northward they rapidly thicken to over 2000 feet near Alston, and to 4000 near Denton and Haltwhistle. Southward they increase to 1800, and then to 2500 at the head of the Eden Valley. Along the northern border of the Lake District the thickness of the same beds varies from 400 to 600 feet; north-west of Appleby they are about 900 feet, but south of that place they thicken to 1800, and east of Sedburgh to 2500 feet (see map, Fig. 20).

From these facts it appears that a pre-Carboniferous ridge underlies Teesdale, on the borders of Durham and Yorkshire, and that in early Carboniferous time it extended thence to the W.S.W., across what is now the Vale of Eden and across the Cumberland part of the Lake District by Ullswater and Derwentwater; perhaps also through the Isle of Man, as indicated in Fig. 20. In Upper Devonian time the surface of this ridge may have been more or less irregular, but even then its width from north to south must have been small, and as it sank beneath the Carboniferous sea its slopes were graded till they were reduced to long and gentle inclinations of less than one degree.

On the south side the water was certainly clear and fairly deep, for, as Goodchild wrote, "limestones were slowly and quietly deposited, sheet upon sheet, in the form of thin wedges, attenuating gradually toward the north-west. In the south-eastern part of the area the pile of thin wedges of limestone accumulated, with hardly any admixture of mechanical sedimentary matter, till nearly 2000 feet of limestone had been built up."

The organic constituents of these limestones are brachiopods, mollusca, crinoids, polyzoa, corals, and foraminifera, and Goodchild

[1] Communicated to me in 1887, and subsequently published in several papers. See *Proc. Geol. Assoc.* vol. xi. p. 269 (1891).

rightly insisted that "not so much as a fathom of it has any claim to be regarded as a coral-reef. Corals flourished there, and in great abundance as regards both species and individuals, but of coral-reefs there are absolutely none."

From the facts above recorded we gather that the Cumberland ridge was submerged about the time of the *Syringothyris* zone, but that the land south of Settle remained above water till that of the *Seminula* zone. Before passing to other districts it will be convenient to complete the history of the central area by endeavouring

Stanford's Geogl. Estabt., London.

Fig. 20.—MAP OF THE NORTH-WESTERN COUNTIES TO SHOW THE POSITION OF THE PRE-CARBONIFEROUS RIDGE (Goodchild).

to ascertain how much of it was submerged by the sea of the Upper or Viséan limestone. For this purpose we must return to North Wales.

The lowest Carboniferous Beds in North Wales are local deposits of red conglomerate and sandstone, which vary in thickness up to 500 feet, but are often reduced to a mere pebbly layer. The overlying limestones were divided by the late G. H. Morton into four stages, the three lower of which he found to be constant in occurrence and colour along the north coast; the highest or "Black Limestone" is only found in Flint, but he believed it to be represented by the "Purple Sandstone" of the Vale of Clwyd.

These four stages have a maximum thickness of 1700 feet, distributed as follows:—

	Feet.
4. Black (or Aberdo) limestone	200
3. Grey limestone	500
2. White limestone	600
1. Brown limestone	400

The more recent researches of Messrs. W. Hind and J. T. Stobbs[1] have shown that the brown limestone corresponds with the highest part of the *Seminula* zone, the white and the grey representing the *Dibunophyllum* zone, and the Aberdo Beds forming a still higher zone of *Cyathaxonia*. All the lower zones are absent, and it is clear that it was only toward the close of the *Seminula* phase that this area was invaded by the sea. Beach deposits were then formed here and there, but so little detritus was carried off the subsiding land by rivers or streams that limestone could be formed in clear water close to the shore, and its accumulation was only occasionally interrupted by the deposition of pure sandstone.

These conditions are well illustrated in Anglesey. Carboniferous rocks occupy part of the northern coast, and pass southwards in a narrowing strip across the island. They consist in the lower part of red and grey sandstones with a basal conglomerate: in Lhgwy Bay these beds are 600 feet thick, and are succeeded by about 700 feet of limestone. When traced southward, however, the sandstones rapidly diminish and finally die out at Llangefni, the limestones overlapping them on to the Archæan schists and being at the same time reduced to a thickness of 450 feet.

In Denbigh and Flint the Carboniferous limestones form long, continuous escarpments, one bordering the western side of the Vale of Clwyd to and beyond Ruthin, while, owing to a powerful fault on the eastern side of this Vale, the Carboniferous series is repeated in Flintshire, and extends from the coast at Prestatyn to Llandegla, where it is cut off by the Bala fault, a distance of about 22 miles.

It is continued southward in the Eglwyseg escarpment between Minera and the valley of the Dee, along which tract the limestones are about 1200 feet thick, and still include representatives of the brown, white, and grey divisions. South of the Dee the line is continued to the west of Chirk and Oswestry as far as Llanymynech, on the north side of the Severn valley. Near Chirk, however, there is a rapid, local attenuation of the beds, indicating the existence of a pre-Carboniferous ridge, by which all the lower beds are cut out, so that only part of the upper "grey limestone" passes over it. The white limestone, however, comes in again about 5 miles south of

[1] *Geol. Mag.*, 1906, pp. 385, 445, and 496.

Chirk Castle and continues to Llanymynech, where the total thickness of limestone is 450 feet.

Here the escarpment terminates, and when Carboniferous rocks are again found to the south of the Severn valley and 6 miles S.E. of Llanymynech, they consist of Upper Coal-measures, which cover and conceal any outcrop of the limestone that may possibly exist.

With regard to the area which must originally have been covered by the Carboniferous Limestone in Denbighshire there can be little doubt that it extended southward from the coast and westward from the Vale of Clwyd over the greater part of the county, and on to the high ground which now forms the watershed between the valleys of the Conway and the Clwyd. It is a significant fact that nearly all the pebbles in the basal conglomerates along the Vale of Clwyd consist of red, green, and purple sandstones enclosing Ludlow fossils ; there are none from Ordovician rocks, and few from the Wenlock Beds.[1] The sandstone pebbles are unlike any rock in North Wales, but resemble the highest Silurian Beds in Westmoreland, and in a less degree those of Shropshire. We may therefore infer that such beds existed in Denbigh during the Carboniferous period, and that large portions of them were broken up and destroyed by the advance of the Carboniferous sea.

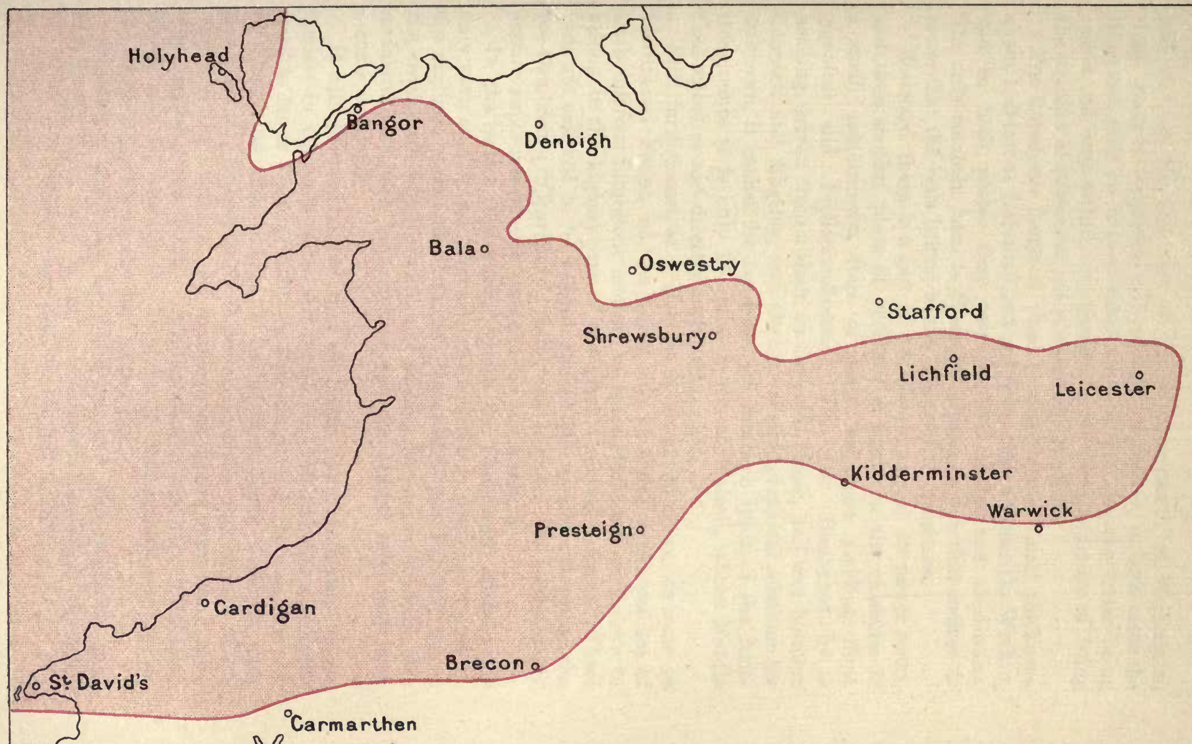
Valuable evidence of the former extension of the Carboniferous Limestone westward into Merioneth is afforded by an outlier, faulted down against Silurian shales, near Corwen, and no less than 12 miles W.S.W. of the Eglwyseg escarpment.[2] Moreover, the thickness here is still considerable, possibly about 500 feet, so that the limestone must have extended some distance farther to the west and south of Corwen. It is hardly likely, however, to have reached so far as the Arenig Mountains, though it may have run up the valley of the Dee as far as Bala ; the northern flank of the Berwyn Mountains probably formed its southern boundary, these mountains forming a promontory which stretched north-eastward towards Llangollen and Chirk, and separated what may be called the Corwen Bay from the Llanymynech Bay (see Fig. 21).

From the facts mentioned above it is evident that the southern shore of this northern Carboniferous sea could not have lain far south of the Severn valley. There are no traces of Lower Carboniferous rocks round Shrewsbury, but farther east at Lilles-

[1] See A. Strahan in *Quart. Journ. Geol. Soc.* vol. xxxv. p. 268.

[2] Messrs. Hind and Stobbs found that the beds exposed in the quarry belong to the highest part of the grey limestone, the subzone of *Lonsdaleia* (in *Dibunophyllum* zone).

Fig. 21.—MAP OF THE EASTERN PART OF ST. GEORGE'S LAND.



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hall and on the east side of the Wrekin (south of Wellington) small tracts of limestone still remain. Moreover, in both cases the limestone rests on beds of basalt and volcanic ash, the latter being coarse and unstratified, and presenting all the appearance of being the product of subaerial, not submarine, eruptions.

The limestones found at these localities are of small thickness, about 150 feet at Lilleshall and not more than 40 near the Wrekin, and in both places they pass up into shales and sandstones. The only common fossil is *Productus giganteus*, but that suffices to prove that the beds belong to the Upper Grey limestone.

Eastward there is a gap of 18 miles occupied by newer rocks, and then another piece of evidence is found in the existence of a small subterranean tract of shaly limestone yielding *Prod. giganteus* and *Amplexizaphrentis*.[1] This was discovered by a heading driven from a shaft on Cannock Chase, half-way between Cannock and Rugeley, and though its stratigraphical relations are unknown, it cannot be far from the southern limit of the limestone, since it is only 10 miles north of Walsall, where Middle Coal-measures rest directly on Silurian rocks.

Still farther east, at a distance of about 30 miles, we come to Charnwood Forest, on the north side of which small patches of Carboniferous Limestone crop up to the surface, and are known to belong to the highest part of the great Derbyshire series. These beds are believed to be bedded against the northern slopes of the pre-Cambrian ("Charnian") rocks, and they are the most easterly surface exposures of such limestone in the Midlands.

In the earlier (Tournasian) epoch the Charnwood district was only part of a broad tract of land which was probably united to the northern mainland of Carboniferous time (see Fig. 23), but at the epoch with which we are now dealing its connection with this mainland may have been severed, and the central land may have become an island.

It will be remembered that we began our examination of its borders in Gloucestershire and traced the Carboniferous sea northward as far as the Clee Hills in Shropshire, and the northern end of Titterstone Clee is only 17 miles from Little Wenlock, near the Wrekin. Consequently it is clear that the tract of land which separated the northern and southern sea basins must have been very narrow at this point. In other words, there was an isthmus, which may be termed the Isthmus of Bridgenorth, connecting St. George's Land with the land to the east.

We do not know how far the Upper Old Red Sandstone, and with it the lower zones of the Carboniferous Limestone, may have

[1] *Quart. Journ. Geol. Soc.* vol. lxii. p. 523.

extended eastward between the Clee Hills and the Dudley district of South Staffordshire, before the erosion and denudation which took place in the interval between the formation of the Middle and Upper Coal-measures. It seems unlikely, however, that the older beds reached nearly so far as Dudley, where the Middle Coal-measures rest directly on Silurian rocks.

Farther east we come to the Warwickshire Coalfield, where Coal-measures of the same age rest on much older rocks (Cambrian), and beyond this, at Sapcote, east of Nuneaton, a deep boring has proved the same superposition of Coal-measures on Cambrian shales, without the intervention of any limestones. But when we reach Northampton we seem to have passed over the eastern border of the Mercian land, and find ourselves once more on ground which was covered by the Lower Carboniferous sea.

A boring at Northampton passed through Lias and a series of sandstones which may belong to the Trias, but are not of a normal character; their base is a conglomerate resting unconformably at 805 feet on Carboniferous rocks,[1] viz. red dolomitic limestone (25 feet) underlain by yellow sandstones and limestones containing Carboniferous fossils, and as these include *Lonsdaleia floriformis* it is fairly certain that they belong to the zone characterised by that form near the top of the series.

Another boring at Gayton, 5 miles S.W. of Northampton,[2] passed through Lias and Keuper red marls, with abnormal basement-beds resting at 699 feet on an eroded surface of Carboniferous rocks. These, however, are quite different from the beds found in the boring at Northampton, being thin limestones and green shales underlain by grey and white sandstones, and finally by red sandstones and marls (with *Modiola Macadami* at 840 feet) down to a depth of 994 feet. These beds cannot belong to any of the upper limestones, but are comparable with the *Cleistopora* zone and the underlying Old Red Sandstone of the Bristol area.

It seems probable, therefore, that between Gayton and Northampton the whole thickness of the Carboniferous Limestone comes in, and that not only was this a part of the Carboniferous sea, but a part of the deeper southern basin, in which deposition had been continuous from the epoch of the *Cleistopora* zone.

Hence we conclude that the Midland area which remained above water during the formation of the higher limestones (*Dibunophyllum* zone) was of comparatively small extent, and was of the nature of a promontory projecting eastward from St.

[1] *Quart. Journ. Geol. Soc.* vol. xl. p. 482 (1884).
[2] *Op. cit.* p. 485.

George's Land, to which it was united by the Isthmus of Bridgenorth. The southern shore of this land must have passed through the central parts of Warwickshire and Worcestershire, whence it curved north-westward toward the south of Shropshire and the Clee Hills.

2. Southern Area.—Having thus dwelt with the geographical history of the central area during the period represented by the Carboniferous Limestone, which is the thickest limestone formation in Britain, we may pass to the southern area and inquire how far this open sea extended to the southward, and whether there is any evidence of its limitation in that direction. The most southerly indication of the limestone facies is at Cannington, near Bridgewater, and when we pass over the broad anticline of the Quantock and Brendon Hills into Devon, a distance of only 16 miles, we find a totally different facies of Carboniferous deposits.

The divisions established for the Bristol area are not applicable to Devonshire, and instead of grey limestones there appears a great mass of black slaty shales (the Pilton and Fremington Beds), surmounted by chert beds and black limestones. Dr. W. Hind has recently shown that these cherts and limestones represent the Pendleside Beds, which elsewhere lie between the Avonian limestones and the Millstone Grit; while on the other hand the Pilton Beds have been claimed as Upper Devonian.

Where, then, is the equivalent of the Carboniferous Limestone in Devon? The Fremington Beds are of small thickness and seem to form beds of passage from the Pilton group to the Coddon Hill Beds. Now Jukes long ago urged that the Pilton Beds were the equivalent of the Carboniferous slate of Ireland, and consequently of the Carboniferous Limestone; Dr. Hind's determination of the age of the beds above the slates certainly goes a long way to confirm Jukes' view, and to make it probable that the passage from Devonian to Carboniferous will be found somewhere in the series which is now known under the name of Pilton Beds. Only a more careful collection and identification of the fossils can settle this point.

The equivalents of the Pilton and Fremington Beds have not yet been determined in South Devon and North Cornwall, where the Chert and Limestone group appears to rest directly and unconformably on red and green slates with Upper Devonian fossils. It is therefore impossible at present to say how far the Lower Carboniferous sea extended southward in that area. It is a fact, however, that there is nothing comparable to the Lower Limestone of Bristol, and the significance of this fact is increased by a consideration of the succession found in Brittany.

The Carboniferous rocks of the N.W. of France are only found in the synclines which lie between the principal anticlinal axes of the country, and the largest area of them occurs in the basin of Finisterre (Western Brittany) ; this basin is connected by narrow but deep flexures with the basin of Laval, where Carboniferous rocks also occur, as they do likewise in the basin of Ancenis, farther south. As all these flexures are of post-Carboniferous date it is probable that the Carboniferous rocks originally spread over all the central and southern parts of Brittany, though they may not have extended far to the northward.

The lower part of this Carboniferous series consists mainly of eruptive materials, quartz porphyries, and volcanic tuffs, with beds of felspathic shales ; the whole group being no less than 3000 feet thick in the basin of Chateaulin. Along the northern border of this basin there are thick beds of conglomerate at and near the base, but these are not found along the southern border. The same is the case in the basin of Laval, where the conglomerates consist chiefly of fragments derived from the older rocks lying to the north. They occur again in the basin of Ancenis, associated with sandstones and lacustrine or lagoonal deposits containing vegetable remains.

This lower group may be of Tournasian age, though it rests with some degree of unconformity on the Upper Devonian. Its sediments were clearly formed in very shallow water, whether fresh or brackish, and the volcanic materials may in great part have been accumulated on an actual terrestrial surface.

These rocks are succeeded by shales with occasional beds of limestone (Schistes de Chateaulin), which yield a Viséan fauna. The limestones are thicker to the eastward, at St. Aubin, d'Aubigny, Changé, and Sablé. There is also a small outlier of limestone with *Productus giganteus* at Regneville near Montmartin in Normandy, but no older limestones occur in that district.

The conglomerates along the northern side of the Chateaulin basin indicate the near neighbourhood of land to the north ; while if there was land to the south it lay somewhat farther from the southern boundary of that basin. Professor Barrois is therefore justified in concluding that in early Carboniferous time a ridge of land lay to the north of the Chateaulin-Laval area, while on the south was a tract of lagoons and marshes which probably bordered another land-tract in that direction.

When this conclusion is considered in connection with the attenuation of the Lower Carboniferous Beds in the north of Cornwall, and with what appears to be an overlap of the Pendleside group on to the Upper Devonian in that area, we have good ground for supposing that in Tournasian time a broad ridge of land occupied the whole area between the Devonshire basin on the north and that of Central Brittany on the south. This land was probably a promontory or peninsula projecting eastward from the Atlantic Carboniferous continent, as indicated on Fig. 23.

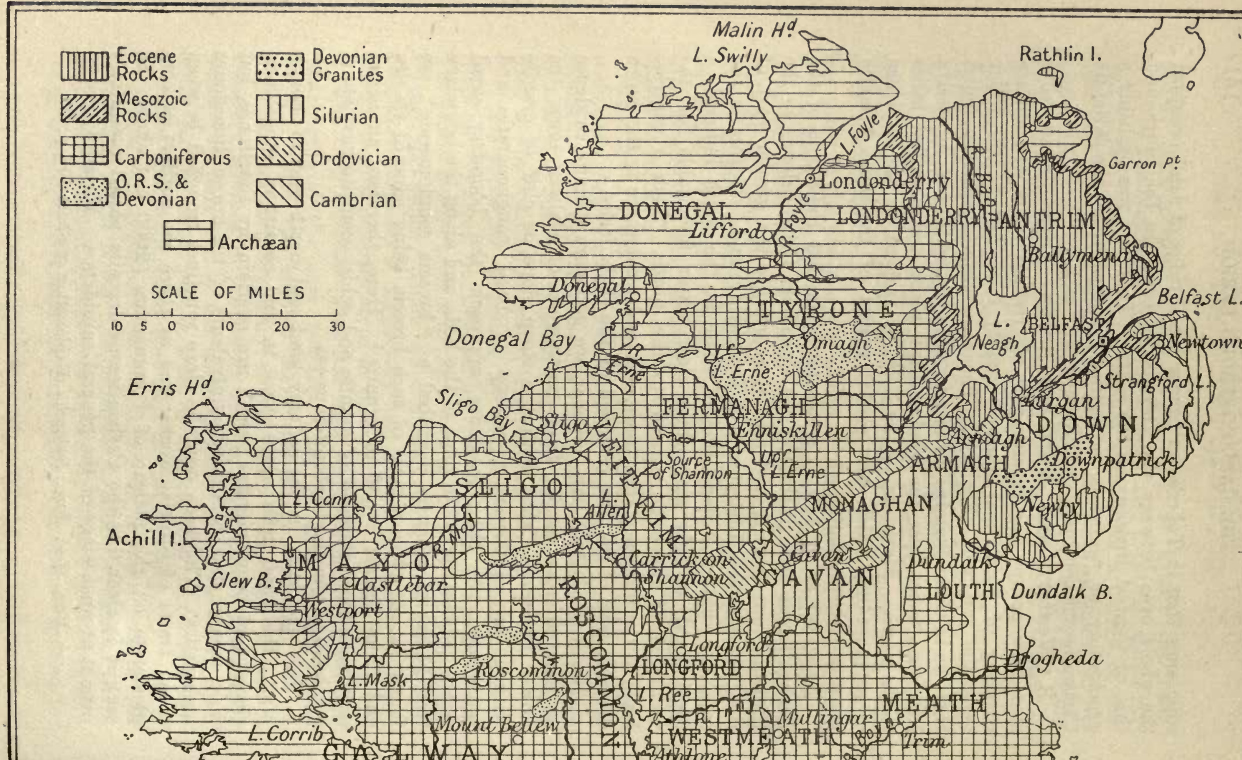
3. Western and Northern Areas.—Carboniferous rocks even now occupy the greater part of Ireland below the surface covering of Drift, and must originally have had a still wider extension (see map, Fig. 22). The same three facies are found there as in Great Britain: a shaly facies in the south-west, a massive limestone facies over the whole central plain, and a mixed facies in the north. Moreover, in the N.W. of Ireland we find evidence of a shore-line which was probably part of the same Atlantic mainland above mentioned.

As stated on p. 112, it seems probable that the whole of the Carboniferous slate (including the Coomhola Grits) belongs to the Carboniferous system, and that it represents the greater part of the Carboniferous Limestones of Central Ireland. If this is the case, the continued deposition of shale in the south indicates a continuously muddy sea, while clear water favourable for the formation of limestone existed to the north. Such a contrast leads to the inference that there was land somewhere to the south or south-west of the area occupied by the shaly facies.

North of Galway Bay, however, we get more definite evidence of Carboniferous land. Thus north-west of Galway town the Lower Limestones abut against a steep slope or cliff of granite without any intervening outcrop of basal conglomerates and sandstones. As the limestones approach the boundary small quartz pebbles appear in some of the beds, and along the boundary line blocks of what is described as "breccia conglomerate" are found, in one place a mass of such breccia being exposed *in situ* and lying against a cliff of granite.[1] Here, therefore, an island or promontory composed of granite and schist seems to have stood out boldly from the Carboniferous sea.

Farther north, in the country west and north-west of Lough Mask, the basal beds again come in and consist of sandstones, shales, and conglomerates, which are overlain by limestones, but may, nevertheless, be littoral equivalents of the lowest limestones and shales. The beds occur in deep synclines troughed between broad tracts of Silurian rocks, and as there are outliers of conglomerate on the plateau of Formnamore (2000 feet above the sea), it is clear that the Carboniferous deposits passed completely over it at some stage of the general subsidence. We are forced to

[1] *Mem. Geol. Surv. Ireland.* Explanation of Sheet 105, p. 20.



Eocene Rocks
Mesozoic Rocks
Carboniferous
O.R.S. & Devonian
Devonian Granites
Silurian
Ordovician
Cambrian
Archæan
SCALE OF MILES
10 5 0 10 20 30
Malin Hd.
L. Swilly
Rathlin I.
Garron Pt.
L. Foyle
Londonderry
DONEGAL
LONDONDERRY
ANTRIM
Lifford
Ballymena
Donegal
TYRONE
Belfast L.
L. Neagh
BELFAST
Newtownards
Donegal Bay
Omagh
L. Erne
R. Erne
Erris Hd.
Strangford L.
Sligo Bay
Sligo
FERMANAGH
Enniskillen
Lurgan
DOWN
Armagh
ARMAGH
Downpatrick
Source of Shannon
Upr. L. Erne
SLIGO
LEITRIM
L. Conn
MONAGHAN
Newry
Allen
Achill I.
MAYO
Carrick-on-Shannon
Cavan
CAVAN
Dundalk
Clew B.
Castlebar
LOUTH
Dundalk B.
Westport
ROSCOMMON
Longford
Drogheda
L. Mask
Roscommon
LONGFORD
L. Ree
MEATH
Mullingar
Mount Bellew
L. Corrib
WESTMEATH
Trim
GALWAY
Athlone

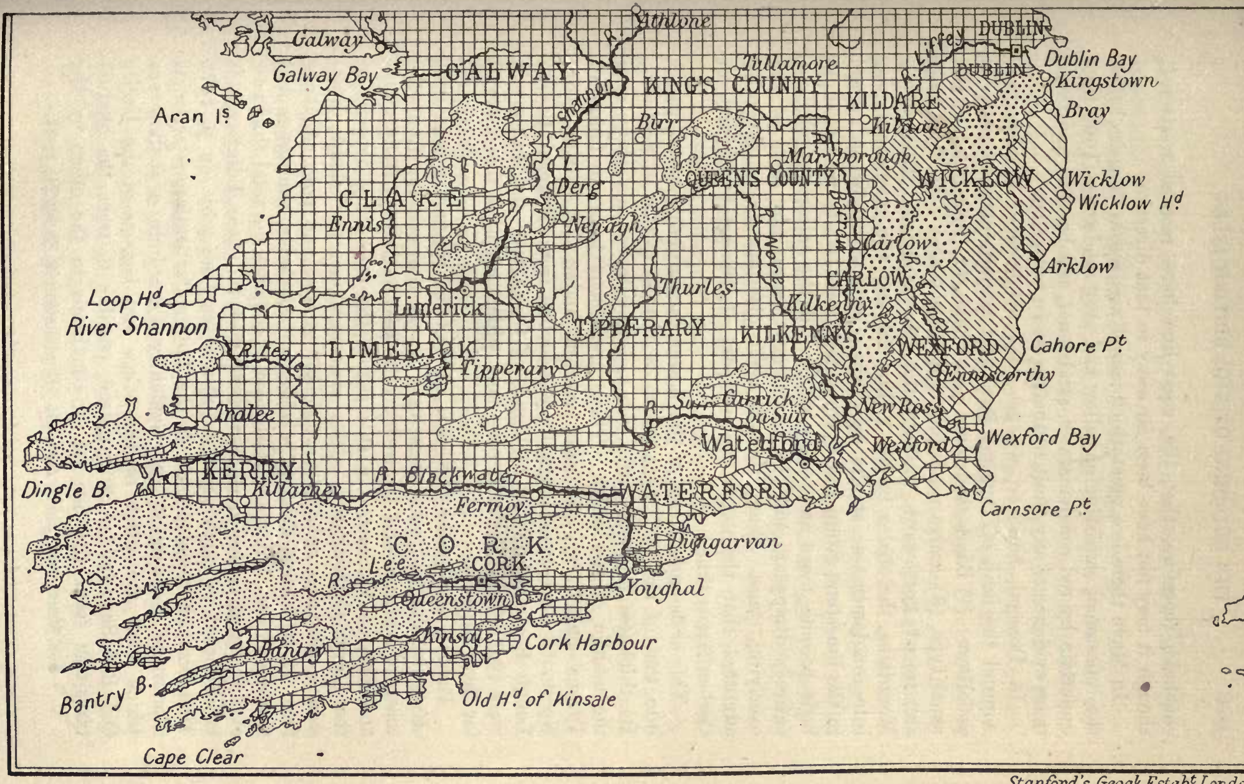


Fig. 22.—GEOLOGICAL MAP OF IRELAND. (Based on the Geological Survey Index Map.)

conclude, therefore, that the coast-line here receded westward, though it may not have been far away in that direction.

In Mayo there is a great thickness of arenaceous deposits below the limestones, consisting of yellow and grey sandstones (1000 feet) underlain by red conglomerates, sandstones, and breccias, and there is no evidence of any limit to their western extension.

In Donegal, however, we get good evidence of a shore-line. Around the head of Donegal Bay the Carboniferous succession is as follows: (1) Basal sandstones and shales, (2) limestones of the usual type, (3) coarse sandstone and shale (Calp). As these beds are traced northward towards the Bluestack and Barnesmore Mountains, the shales in No. 1 thin out and the sandstones pass into conglomerates; at the same time beds of sandstone appear in the limestone group and thicken northward, while the limestone beds become more and more sandy, till the calcareous element entirely disappears and the sandstones merge into those of the overlying stage. From these clear indications it is generally admitted that the north-western part of Donegal was land in Carboniferous time.[1]

This arenaceous facies of the Lower Carboniferous series passes into that of the N.E. area, which is similar to that of Scotland. Its thickness is about 2000 feet, and limestones only occur near the middle of the series. These arenaceous beds are found in Tyrone and Derry, and pass eastward under the Antrim basin. No doubt they were originally continuous from Donegal Bay to Lough Foyle, while the highlands of Glendowan and Inishowen were part of the Carboniferous land which supplied the material for these deposits.

Passing now to the Lowlands of Scotland we find a large area of Carboniferous rocks, stretching across the country from the coasts of Ayrshire and Renfrew on the west to those of Haddington and Fife on the east. In this region the prevailing deposits in the Lower Carboniferous series are sandstones and shales, limestones occurring only in the highest groups, and only as bands from 12 to 30 feet thick in a succession of shales, sandstones, and Coal-measures. In the western part of the area the total thickness of this series is not more than 5000 feet, but near Edinburgh it is estimated to reach about 9000 feet (see the table on p. 137). This Scottish development of the Lower Carboniferous series is interesting, because it was evidently formed in a shallow sea which took the place of the lakes and lagoons of the Upper Old Red Sandstone. It is, indeed, possible to trace the gradual transition from the one set of conditions to the other by the

[1] See *Mem. Geol. Surv. Ireland.* Explanation of Sheet 24, p. 25.

peculiar characters of the deposits which succeed the Old Red Sandstone.

The lowest member of the Scotch series is the Calciferous Sandstone, and at the base of this are the Ballagan Beds. Of the conditions under which these beds were formed, Goodchild has given the following description: "They appear to have been extensive mud-flats which were maintained at or near the sea-level by the deposition of mud, silt, and sand, at a rate which nearly always kept pace with the rate of subsidence. They may be likened to those which are found at the present day in the Runn of Cutch. An occasional subsidence more rapid than usual admitted the sea; while local changes in the direction of the currents, or else inequalities of subsidence, isolated small areas of sea-water in one part, and of river water in another part, and left them in that condition, while adjoining parts, perhaps only submerged at spring-tides or after heavy floods from the land, became dry in the sun. Hence abundant sun-cracks were formed in the clays, and these often became filled with sand blown into them by the wind from the adjoining areas, and were thus saved from obliteration. An occasional shower pelted the surface of the mud and left its record in the shape of the well-known rain-prints. Areas of sea-water, temporarily cut off in the lagoons, deposited gypsum crystals and occasionally even rock-salt."

In some parts of the area, as in the Campsie and Kilpatrick Hills and near Edinburgh, volcanic eruptions took place both during and after the deposition of the Ballagan Beds. Lava flows issued from many volcanic vents, and now form sheets of basalt interbedded with sandstones and with beds of siliceous sinter and tufaceous limestone, which are evidently the products of thermal spring-waters.

After this volcanic episode the area was again invaded by the sea, and a thick series of shallow-water marine and estuarine deposits were formed, chiefly sandstones with occasional beds of shale. Much calcareous matter was also present in solution, and was frequently precipitated to form calciferous sandstones, the sand grains being cemented together by crystalline calcite.

The succeeding Oil Shale group is a more local set of deposits. Its thickest devolopment is in the Lothians and in Fifeshire, and it thins out entirely to the westward, and also to the south of Edinburgh, though it reappears in Berwick and Northumberland as the Scremerston Coal series. It seems, therefore, to have been a deposit formed during a subsidence of the eastern side of the Scottish area, bringing in the waters of the deeper sea, which lay to the south and south-east of that area, and in which the great mass of the Carboniferous Limestone was being accumulated.

During all this time the amount of sediment poured into the area of deposition from the surrounding land seems always to have been merely enough to counterbalance the effects of subsidence, and to keep the water shallow. Moreover, throughout this epoch volcanic activity continued to be rife, and the lowland area seems to have been broken up into a number of waterspaces divided by low banks and ridges, from which rose dozens of small volcanoes; these either singly or in groups ejected lava and ashes, and then became inactive, allowing other vents to form and take up the rôle of action. In other words, the vulcanicity was of the Puy type, like that of Auvergne and Velay in Tertiary times.

At length it would seem that subsidence became more rapid, or more probably the central area was farther removed from the sources of deposit, so that it was overspread by a deeper sea; calcareous organisms, such as Crinoids, Corals, and Brachiopods, were then able to live in large numbers, and to build up beds of limestone, though these only occur at intervals, and are seldom more than 30 feet thick. It is certain, however, that the physical conditions were becoming more uniform over the whole area, for the three highest beds of limestone, though only 3 or 4 feet thick, have been traced over an area of at least 1000 square miles.

We have now to consider what were the limits of this Scottish part of the Carboniferous sea, and more particularly how far it spread northwards on to the Highlands at the time of the greatest submergence. The tracts of the Carboniferous rocks which occur in Cantire and the Isle of Arran, as well as the resemblance between the Scottish deposits and those of the north of Ireland, make it certain that the sea in which they were formed stretched continuously across the intervening spaces. So great has been the erosion and detrition which the more northern parts of Scotland have undergone that we might well have been left without any actual evidence of the further northern extension of this sea; but it so happens that small remnants of Carboniferous rocks exist as far north as Morvern and the Bridge of Awe.

A small exposure of sandstones yielding plants of Coal-measure age was discovered by Professor Judd on the foreshore of Ardtornish, opposite the Isle of Mull,[1] and this remained the only piece of evidence until 1898, when fossils were obtained from a patch of red marls, sandstones, and conglomerates at the Bridge of Awe in Lorne;[2] the plants in these beds have a Lower Carboniferous facies, and are associated with a shell rather doubtfully considered to be *Modiola Macadami*, which has recently been recognised as

[1] *Quart. Journ. Geol. Soc.* vol. xxxiv. p. 684.
[2] *Sum. Prog. Geol. Survey* for 1898, p. 129.

a common fossil in the lowest marine beds of East Fife, East Lothian, Berwick, and Liddesdale.[1] The beds rest on the lavas of the Lower Old Red Sandstone, and are faulted against the schists of the Pass of Brander.

From the evidence of these two outliers we can hardly doubt that deposits both of Lower and Upper Carboniferous age spread over the whole of the area which intervenes between the Firth of Clyde and the district of Morvern ; by analogy also we may infer that they had a similar extension all across Scotland to the northward of their present line of boundary ; in other words, that they originally covered the greater part of Perth and Forfar, and spread as far as the southern slopes of the Grampians or Central Highlands.

By this we do not mean that the Carboniferous strata rested on the schistose rocks which now form the Grampian Mountains ; in all probability there was little of this region which was not covered by the Lower Old Red Sandstone, and it would be rocks of this age that formed the shore of the Carboniferous sea. The influence of this shore-line seems to be exhibited in the arenaceous character of the beds in the north-east of Fife, which represent the Oil Shales of the Lothians, for these shales thin out northward and are largely replaced by sandstones and grits in the north of Fifeshire.

A consideration of all the facts above mentioned lea. us to think that the coast of the Carboniferous continent ran northward from Donegal outside the shores and islands of Argyll, reaching perhaps even farther north than Mull and Morvern in the form of a bay, but eventually bending south again and then passing eastward on the southern side of the Central Highlands, out through Kincardine into the area now covered by the North Sea. The increase in the thickness of the sediments, and particularly of the sandstones in passing from the west to the east of the Lowlands and from the south-west to the north-east of Fife, indicates that the main source of supply lay in those directions, and consequently we may infer that a large part of the North Sea region was land. Probably the Scottish Sea terminated in a land-locked gulf, which stretched north eastward into the land, and into this gulf one or more large rivers must have emptied themselves, bringing much sand and mud from the land to the north and north-east (see map, Fig. 23).

The entire absence of Carboniferous rocks over the whole of

[1] See "The Geology of East Fife," by Sir A. Geikie, *Mem. Geol. Surv. Scotland* (1904) ; also Messrs. Peach and Horne, "The Canonbie Coalfield," *Trans. Roy. Soc. Edin.*, 1903, p. 835.

Scandinavia, Lapland, and Finland renders it highly probable that all this region formed part of the northern continent which stretched across the North Atlantic to include Greenland and the greater part of Canada. In the North Sea area the coast-line probably ran south eastwards outside the limits of our islands, and then seems to have passed eastward through the centre of Denmark, and across Northern Germany into Russia.

We may next consider whether the Scottish area of deposition was ever completely merged into that of Northern England during the progress of the great subsidence ; whether, in fact, the higher subdivisions of the Lower Carboniferous series spread completely over the Southern Uplands of Scotland, or whether some parts of these Uplands always remained as an island or islands in the Carboniferous sea.

There is no doubt that an early connection was made between the Scottish and Northumbrian basins round the eastern side of Berwick and Haddington. Lower Carboniferous rocks occupy the southern border of Scotland from Berwick to Solway Firth, and recent borings at the northern end of the Isle of Man have revealed the existence of these rocks far below the level of the sea.[1] Small tracts of the basal sandstones occur on the south coast of Kirkcudbright, and finally a narrow tract of sandstones and shale belonging to some part of the Lower Carboniferous series borders the Permian on the western side of Loch Ryan (Wigtonshire). It is evident, therefore, that the broad tract of Silurian and Ordovician rocks which forms the Southern Uplands must have been completely surrounded by Lower Carboniferous deposits, and the only question is, How far did they spread on to the higher ground ? The answer seems to be that they never covered the whole of it.

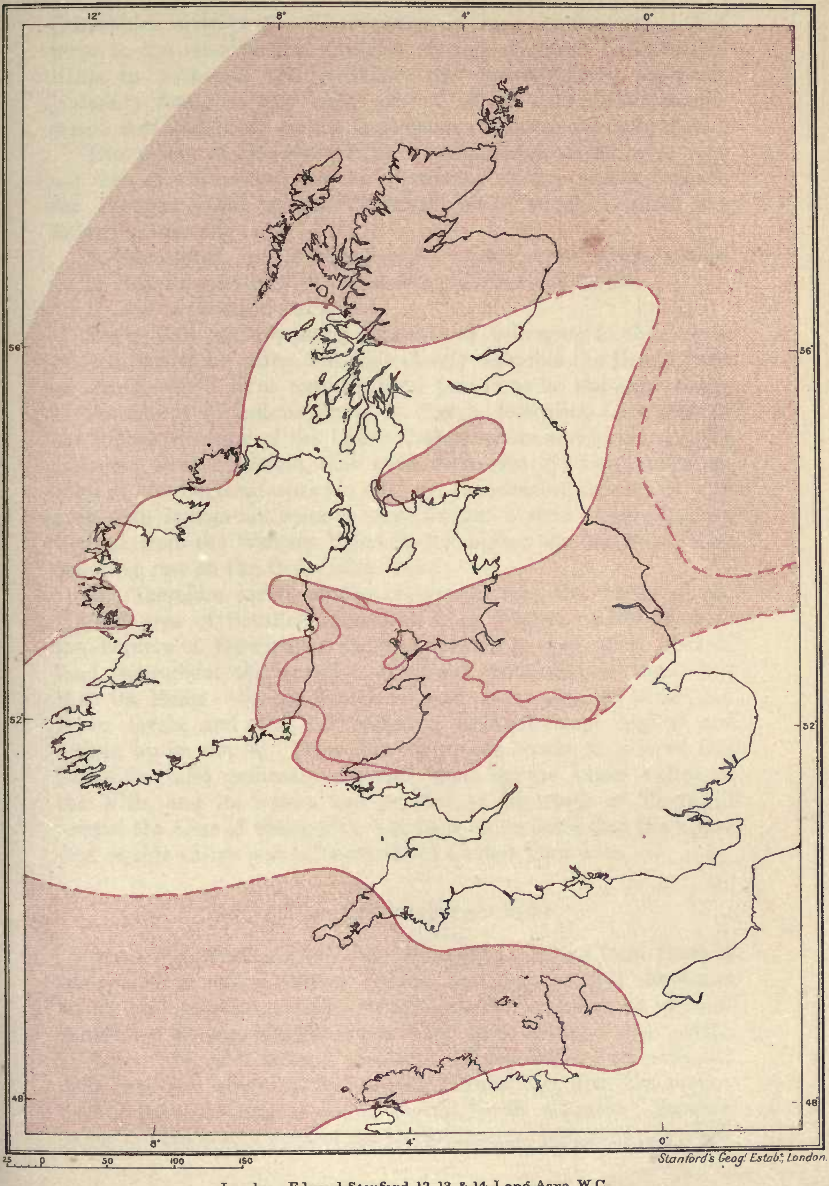
Describing the basal conglomerates of the series in Dumfries, Lanark, and Edinburgh, the Geological Surveyors say: "These conglomerates continue to fringe the Carboniferous area while the strata above them pass quite away. Hence, in this continuous band of conglomerate, one portion is on the horizon of a low part of the Calciferous Sandstone series, while another portion is on the horizon of some of the higher members of the Carboniferous Limestone series. It thus brings before us evidence of shore conditions during a protracted submergence of this area."[2]

In the south of Edinburgh indeed there is proof that the whole of the beds which underlie the Limestone group have thinned out before reaching the great boundary fault, for south of Magbiehill an outlier of the Limestones rests directly on the Lower Old Red

[1] See "Geology of the Isle of Man," *Mem. Geol. Survey* (1903).

[2] *Mem. Geol. Surv. of Scotland.* Explanation of Sheet 15, p. 30.

Fig. 23.—GEOGRAPHY OF LOWER CARBONIFEROUS TIME.



London: Edward Stanford, 12, 13, & 14, Long Acre, W.C.

Sandstone, without the intervention of any conglomerate; the same is the case in the Douglas district of South Lanarkshire, while in Nithsdale the limestones end abruptly along the great boundary fault, on the south side of which only Coal-measures occur, resting directly on the Ordovician rocks around Sanquhar.

The valley of the river Nith, however, appears to be a very old line of depression, for an interesting outlier occurs beneath the Permian rocks of the Thornhill basin, which exhibits the following succession :—

3. Sandstones, red, grey, and white, with red and purple shales.
2. Red limestones with Carboniferous limestone fossils.
1. Red sandstones and shales.

These beds were formerly regarded as belonging to the lowest or Red Sandstone group, but they closely resemble the Corrie Beds of Arran, which have recently been proved to be the equivalents of the Lower Limestone group of Scotch geologists, *i.e.* a part of the highest division of the Lower Carboniferous series (see p. 137). It would seem, therefore, that even Nithsdale did not become an inlet of the Carboniferous sea till near the close of this epoch, and even then it does not seem to have formed a strait separating the Central from the Western Uplands, for higher up the Dale Coal-measures rest on the Ordovician rocks.

We therefore arrive at the conclusion that the whole of the Upland area of Southern Scotland, from Wigton on the west to the borders of Berwick on the east, formed a continuous tract of land throughout the duration of Lower Carboniferous time; but that its limits were gradually reduced as it sank to lower and lower levels, and the Carboniferous deposits crept higher and higher up its slopes. From the sea on the southern side of this island an inlet gradually extended itself up the broad valley of the Nith, and its waters had reached as far north as Thornhill toward the close of the epoch; but there is no proof that the upper part of this valley was submerged till a much later date.

B. *Upper Carboniferous Time*

The Carboniferous rocks differ in certain respects from those of the preceding and succeeding systems, and they exhibit characters which can only have resulted from a general uniformity of physical conditions having prevailed over very large areas of the earth's surface. The same general succession of deposits is met with, not only over the whole of the British Islands, but over the greater part of Northern Europe and of central North America. Furthermore, the fauna and flora of the Carboniferous rocks are everywhere similar, and are everywhere persistent throughout a great thickness of strata.

In Britain a few species are indeed confined to the lowermost marine beds, and a few to the highest marine beds—to beds, in fact, which were formed when the physical conditions were undergoing a change, and when the forms would necessarily be most liable to variation. Some of the Corals and Crinoids—which were the chief contributors to the formation of the limestones—are naturally most abundant in those limestone masses; but most of the Mollusca and Brachiopoda have a great vertical range, some of them extending from top to bottom of the marine series, and recurring in the marine bands which are intercalated at intervals among the essentially freshwater and estuarine strata of the overlying Coal-measures.

From these facts we may conclude that the physical and geographical changes which took place during the course of the period were very gradually accomplished, and did not for a long time cause any material alteration in the climate or conditions of existence. A great change, however, did occur in the middle of the period which produced a general shallowing of the water, and led to a great extension of those shallow-water sandy and shaly deposits which had hitherto only been formed round the margin of the continental land. After this change sands, and in many places very coarse sands with small pebbles of quartz and felspar, were deposited over the whole of those wide areas of the Carboniferous sea-floor which had previously been covered by clear water, and had been laboratories for the formation of pure limestone. This, moreover, was no local change, but one which affected the whole of the north European region, and led to the formation of that wonderful series of shales, clays, sandstones, and coal-seams which are commonly called the Coal-measures.

Professor Green has pointed out that the great series of beds which compose the divisions of the Millstone Grit, the Lower and the Middle Coal-measures, have so many common characteristics "that it is impossible to resist the conclusion that they were all three formed under substantially the same conditions, and that these conditions were altogether different from those which gave rise to the Carboniferous Limestone and the Yoredale rocks." [1] He thought the change was caused by the blocking up of the communications between the inner and the outer sea, so that the former was converted into a large freshwater lake; but though this might account for the succession in the principal English and Scotch coalfields, it is far too local an explanation to

[1] *Coal, its History and Uses* (1878), p. 50.

account for the Irish, French, Belgian, and other European Coal-measures.

Since Professor Green wrote, our knowledge of the Carboniferous succession has been made more complete by the researches of Dr. W. Hind, Mr. J. A. Howe, Dr. A. Strahan, Mr. W. Gibson and others. In Lancashire, Flintshire, the Isle of Man, S.W. Yorkshire and Derbyshire, there is a thick group of beds lying between the "Avonian" limestones and the Millstone Grits. To these beds Messrs. Hind and Howe have given the name of the Pendleside Group, and the following is condensed from their description of its lithological characters. It consists of dark shales and limestones with occasional sandstones and mudstones. The limestones are in thin beds, dark grey and often black, while those of the great limestone *massif* below are greyish white. The beds are lenticular, and the limestones often pass into calcareous shales with "bullion" nodules. Plant remains are common, both shales and limestones being usually black, with coaly particles and carbonaceous matter.

There appears also to be an actual break between the main mass of the Avonian limestones and the Pendleside Beds, the latter in several localities resting on an uneven surface of the former. The phenomena appear to be those of so-called "contemporaneous erosion," that is of erosion by current action before the deposition of the Pendle Shales. Moreover, there is a palæontological as well as a physical break at the same horizon, for a number of common Carboniferous Limestone species seem to die out, and a special group of Cephalopoda come in with the Pendle Shales, the fauna of the group being essentially the same as that of marine beds in the overlying Millstone Grit and Lower Coal-measures, so that it must be included in the Upper Carboniferous series.

Whether the Pendleside Beds are equivalents of the Yoredale Beds of North Yorkshire and Durham, or overlie them, as Dr. Hind thinks, has not yet been ascertained; but there seems no doubt that the former contain a fauna which marks them as later than the highest Avonian limestones, so that if this fauna is found also in the Yoredale Beds, they too must be newer than the *Dibunophyllum* and *Cyathaxonia* zones.

Let us now consider the characters and distribution of the Millstone Grit group of the same northern area. This group consists of several massive bands of coarse sandstone or "grit," divided by bands of shale; some of the grits reaching a thickness of 400 to 500 feet. The quartz-grains of which they consist are generally little worn, often subangular, and not seldom of large size, though the grain varies much at different places in the same grit band.

Messrs. Hind and Howe point out that the greatest development of the Millstone Grits coincides very closely with that of the Pendleside group; the maximum of the former lying between Pendle Hill and Kinderscout, in which district the group has a total thickness of about 3500 feet. From this centre the group thins in all directions, except toward the east, in which direction, however, it cannot be traced very far. Southward this great lenticular mass thins till it is only 200 feet thick at Mow Cop in North Staffordshire, and about the same in Leicestershire. In North Wales its representative, the Gwespyr sandstone, is only 300 feet in Flint, and thins to a few feet only in Denbighshire.

To the northward the Grit series is traceable all through Yorkshire, but the grit bands diminish rapidly both in number and thickness, and also become finer in grain, so that in Durham they are indistinguishable from the flagstones of the Lower Coal-measures. In Scotland, though bands of sandstone occupy the position of the Millstone Grits, it is doubtful whether they are the actual equivalents of this group. Dr. W. Hind has recently shown that the marine fauna found in the associated shales is not that of the English Millstone Grit, but resembles that of Coal-measures of Nebraska, U.S.A., and of a band at the base of the Bristol Coal-measures. With regard to the Flagstone group of Ireland, since the Pendleside Beds do occur beneath it, there is more reason to regard it as representing the Millstone Grits.

Not only are the grits themselves thickest in Lancashire and South Yorkshire, but in one of them (the Kinderscout Grit) the grains and small pebbles become larger as it is followed eastward. Southward, though some of the grits thin out, those that remain are more or less coarse. South-westward in North Wales, though thin, the sandstone has a pebbly grit at the base and other pebbly beds higher up, and it is overlapped westward by Coal-measures with a pebbly base resting on the Limestones.

Thus, though the land which lay to the southward may have furnished some of the sandy and pebbly material, all the facts indicate that the greater part of it came from the eastward. Many years ago Dr. Sorby made a study of the current bedding of the grits along a tract of about twenty-five miles in North Derby and South Yorkshire;[1] his observations showed that the currents which brought the sand flowed from north-east to south-west. He also examined the small pebbles in the grits, and

[1] *Proc. Yorks. Geol. and Pol. Soc.*, 1859, vol. iii. p. 672.

found that the commonest were of quartz, like that which occurs in coarse-grained granite, while there were many of orthoclase felspar, and he obtained a few bits of the actual granite from which the quartz and felspar had been derived. There were also pebbles of quartz-rock, of a kind of eurite, of a syenitic rock, and of clay slate. On comparing the bits of granite with some specimens of Norway granite, he found they were so similar that they might have been portions of the self-same rock. On the contrary, the difference between them and any of the English granites known to him was equally striking, and he concludes that "the materials of the Millstone Grit in South Yorkshire were derived from the waste of a south-westward prolongation of an ancient Scandinavia, the site of which is now occupied by the North Sea" (*op cit.* p. 675).

Messrs. Hind and Howe concur in this opinion, and remark "that the pebbles and quartz of the Millstone Grit series could only have been derived from land lying to the east and north-east; probably from a continent which included Scotland and Scandinavia. The source of the Millstone Grits must have been largely a granite area, for mica and felspar, the latter sometimes decomposed into china-clay, are found abundantly in certain of the beds. The Pendleside group was probably derived from the same direction, and was laid down farther from the shore than the Millstone Grit, and therefore the whole of the deposits indicate a slowly rising area" (*op cit.* p. 392).

This was indeed the conclusion at which I had arrived in 1892, when the last edition of this book was issued, as the following extract will show ; after mentioning the suggested sources of the Millstone Grit, I wrote :—

"Even then, however, we cannot understand the superposition of coarse sandstones upon a limestone-and-shale series without assuming that great changes took place in the physical geography of the area. During the formation of the lower limestones the brooks which drained the central island can hardly have carried any sediment to the sea, their waters must have been clear, and the rainfall must have been small ; later on, however, they seem to have carried both mud and sand, and eventually their volume and velocity were so increased that they could transport coarse sand to very great distances. I see only one way in which such a change could be brought about, and that is by a general and considerable elevation of the area, raising the central parts of the island into those atmospheric regions where rain, frost, and wind are most vigorous and incessant in their action."

The effect of this uplift on the mainland to the east and north-east would be to bring the actual shore-line nearer to the British area, and to enable the rivers of that land to carry their sediment farther and farther westward over the English area of deposition. It was, therefore, by this general elevation of the region and by the consequent great extension of the river-deltas, and of the river-deposits in the shallowing sea, that the change from Lower to Upper Carboniferous conditions was accomplished. So far did this filling-up process go on that parts of the sea-floor became shallow enough for the growth of terrestrial plants, for actual seams of coal occur in the highest part of the Millstone Grit series in Lancashire.

When dealing with the geography of the earlier part of the period (see p. 148), we inferred, mainly from the results of borings near Northampton, that St. George's Land and the Midland ridge formed an island which terminated near Leicester, and was not a peninsula connected with the mainland on the east. It is, however, very probable that the upward movement which supervened had by the time of the Kinderscout Grit effected a union between the eastern land and the central island, converting the latter into a long peninsula and the northern area of deposition into a shallow land-locked bay. If this were the case, the only communication between this northern area and the open sea to the south would be round the western end of St. George's Land through the central and southern parts of Ireland.

Such geographical conditions will enable us to understand how it is that both the Pendleside and Millstone Grit groups have their maximum development in the northern basin, and why the so-called Millstone Grits of the southern area cannot be definitely correlated with those of the northern. The tracts of granite from which the northern grits were principally derived must have existed in that part of the eastern land which was adjacent to the northern gulf, and the watershed of the land must have lain to the south of them, for in Belgium and the north of France there is nothing comparable to the Millstone Grit between the Lower Coal-measures and the representatives of the Pendleside Beds.

We must now briefly consider the southern area of deposition, where the lithological development is more variable than in the northern. Thus in the Bristol district, though shales occur between the Avonian limestones and the Millstone Grits, they contain the fauna of the *Dibunophyllum* zone, and not that of the Pendle Shales, so that if the latter are represented at all it must be by the lower part of the grits, just as in Dean Forest the *Dibunophyllum* zone seems itself to be represented by grits.

In South Wales, however, the Pendleside Beds are again recognisable. In the Gower peninsula, S.W. of Swansea, there is a complete passage from black limestones and shales with a *Dibunophyllum* fauna into black shales and chert beds with Radiolaria and Pendleside fossils. The same succession is found in Pembrokeshire. Here also it is interesting to find a close association between the Pendle Shales and the so-called Millstone Grits, for the Survey officers are inclined to think that the grits of the northern side of the Glamorgan coalfield are partly replaced by these shales on the southern side. On the northern side Radiolarian cherts are found only a few feet below the basal grits, above which are a series of shales and grits with a thick sandstone (the Farewell Rock) at the summit; in the southern area no such basal grits are found, and there is at least 1000 feet of shales above the Chert Beds.

The grits along the northern outcrop vary much in thickness and in degree of coarseness. They are thin but coarse on the eastern side of the Glamorgan coalfield, and also in Pembrokeshire, having their maximum development of about 1300 feet near Ammanford. The grits are of various colours—dark grey, green, and brown being the prevalent tints. There can be no doubt that the constituents of these beds were derived from the land which lay to the north.

In Devonshire the equivalents of the Pendleside group are found in the Coddon Hill Beds, which consist of Radiolarian cherts and siliceous shales, and in the overlying black limestones with *Posidonomya Becheri*. These beds can be traced all across North Devon from Barnstaple to Bampton, and they crop out again on the south side of the broad syncline along the borders of Dartmoor. The overlying beds are known as Culm-measures, but near Instow and Tawstock in North Devon there are grey and greenish sandstones, which may represent the Millstone Grits as they underlie beds with marine fossils which seem to represent the Lower Coal-measures.

We have next to consider the conditions under which the great series of Coal-measures were accumulated. These beds have been divided into Lower, Middle, and Upper, but as the first two everywhere form a continuous series it will be convenient to consider them as one group. Indeed, in the Bristol coalfield, the so-called Lower measures seem to represent both the Lower and Middle series of the Midlands; in that area the total thickness is reckoned at 2500 feet, but in South Wales it varies from 3000 to less than 1000. In North Staffordshire the thickness of the so-called Middle and Lower groups is about 4000, in Lancashire 5000, and in Yorkshire 4500.

The deposits to which the term "Coal-measures" is applied consist of a succession of sandstones, shales, clays, and coal-seams alternating with one another, the seams or layers of coal being frequent, but varying greatly in thickness from a few inches to several yards.

Coal, as is well known, consists of compressed vegetable matter which has undergone certain chemical changes in the course of time. Many of the intervening shales and sandstones are crowded with the remains of terrestrial plants, and the clays which underlie coal-seams often contain roots of the tree-like plants which grew in them and contributed to the formation of the overlying coal. Most coal-seams have probably been formed by the decay of such vegetation *in situ* and in coastal swamps where the water was sometimes fresh and sometimes brackish ; but some seams appear to be regularly stratified and laminated, and these are probably accumulations of drifted vegetable matter.

The trees and plants which grew in these Carboniferous swamps were for the most part very different from any existing forms. In general aspect, however, the swampy areas must have greatly resembled those which border low-lying tropical coasts and form the deltas of tropical rivers at the present time ; areas where monotonous expanses of dense vegetation are broken only by muddy lagoons, and an intricate system of tidal waterways, often narrowed by encroaching mangrove trees.

The most conspicuous trees in the Carboniferous swamps were the Lepidodendron and the Sigillaria. The former were gigantic members of the Lycopod family, and grew to a height of 50 or 60 feet. The Sigillaria was also a Lycopod, but of a different growth, and had long branching roots (*Stigmariæ*) which spread out in all directions. These roots may possibly have been partly aerial, like those of *Sterculia* and *Sonneratia* rising well above the low-water mark of the swamp, and uniting in a dome-shaped manner to support the trunk.

Giant Equisetums (*Calamites*) flourished in the shallow waters, and numerous fern-like plants grew on the drier spots and on the trunks of the trees (both dead and living), just as certain ferns and epiphytes do at the present day. Fig. 24 is an attempt to portray the appearance of this Carboniferous vegetation, copied from a pictorial reconstruction by Dr. Potonié, a well-known German authority on fossil plants.

Some of the shales and sandstones are doubtless of estuarine origin, others may have been deposited in open lagoons, but some beds are purely marine ; moreover, these marine bands recur at intervals throughout the whole series, and recently it has been

Fig. 24.—AN IDEAL VIEW OF CARBONIFEROUS VEGETATION (after Dr. Potonié).

shown that some of them are persistent horizons traceable not only through one basin but through several, thus proving these basins to be parts of one originally continuous whole. In North Staffordshire, for instance, no fewer than nine marine bands have been found, and at least three of these have been identified in the Lancashire, Yorkshire, and Nottingham coalfields.

While, therefore, the Millstone Grits mark a general and rather rapid upheaval of the whole British region, the vertical amount of the uplift cannot have been very great; and it is evident that the movement exhausted itself before the Coal-measures began to be formed, for these were undoubtedly deposited during a gradual and general subsidence, and it is interesting to note how this subsidence is attended by a reverse change in the texture of the sandstones. In the Lower Coal-measures sandstones still play an important part, but they are less coarse in grain; in the Middle group thick beds of sandstone are few, and all the sandstones are fine-grained. As Professor Green remarks: "The gradual subsidence and the ceaseless wear and tear of atmospheric denudation gradually lowered the elevated tracts, so that they were acted on less vigorously by subaerial agencies; at the same time the rivers, descending by gentler gradients, lost by degrees the power of moving coarse heavy detritus. So, with the lapse of years, the amount of sandy sediment gradually grew less and less, and sandstones formed a gradually decreasing item in the deposits in process of formation." (*Coal, its History and Uses*, p. 61.)

In spite of the submergence, however, large tracts of the sea-floor were repeatedly silted up and converted into marshy flats, where the materials for the beds of coal were accumulated, though the tracts on which the plants grew were evidently never raised much above the mean level of the sea. It is not improbable that the coal-seams mark pauses in the progress of the subsidence, while the marine bands indicate times when the downward movement was more rapid than usual, causing the sea-water to break in and overflow the wide alluvial levels.

A plain proof that the Coal-measures were formed during subsidence is afforded by the fact that the Middle Coal-measures of the Northern area overlap the Lower measures southwards, so as to rest directly on the older Palæozoic rocks in Warwickshire and South Staffordshire. It seems likely that during the deposition of these measures the whole of the central ridge from Leicestershire to South Shropshire and the borders of Hereford was reduced to the condition of swampy ground. At the same time all the deeper parts of the Carboniferous sea seem to have been filled up by the sediment which had been so continuously poured into them;

so that practically the whole of England and the greater part of Ireland had been converted into one vast area of low-lying swampy flats, river-ways, and lagoons.

The only tracts within this great region of swamps which may have remained in the condition of dry and solid ground are the central part of St. George's Land, including the central part of Wales, and parts of the Southern Uplands of Scotland.

The higher parts of the Scottish Coal-measures are now regarded as equivalents of the Middle series in England, and it has been proved recently that the outlying coalfield of Sanquhar in Dumfries contains representatives both of these and the Lower Coal-measures. This coalfield lies in the old pre-Carboniferous valley of Nithsdale at a comparatively low level, and consequently it is probable that the much higher ground both to the east and west of Nithsdale was still a dry land surface rising above the general level of the surrounding swamps.

Whether any high land existed to the south of Devonshire at this time is uncertain in the present state of our knowledge, but the conglomerate at the base of the barren Coal-measures in South Devon suggests that there was. Moreover, in Brittany there is very little to represent any part of the Upper Carboniferous series; nothing comparable to the Millstone Grit or to the Lower Coal-measures exists. The Teillé Beds, which consist of alternations of shales and conglomerates, may be equivalent to the higher part of our Middle group, and the presence of conglomerates indicates the near neighbourhood of land. This land probably lay to the north, including parts of Northern Brittany, Normandy, and Cornwall, with the intervening Channel area.

Most of Southern England, however, was part of the great area of deposition, as proved by the existence of Coal-measures below Burford in Oxfordshire and below the eastern part of Kent. But this great development of Coal-measures is by no means peculiar to Britain; coalfields are found in many parts of the Continent, notably in France, Belgium, Germany, and Russia, everywhere presenting a similar aspect and a similar succession of measures, making it certain that they belonged to one natural province or geographical area.

We must conclude, therefore, that over a large part of what is now Europe there existed vast tracts of alluvial land but little above the sea-level, the conterminous deltas, in fact, of the rivers which drained the surrounding land, just as Holland is the conterminous delta of the Rhine, Meuse, and other rivers. It is as if an area as large, or larger, than that covered by the Mediterranean Sea were slowly silted up and converted into one enormous swamp. To bring about such a result there must have been many rivers of large size emptying themselves into this sea, rivers comparable to the largest which now exist in the world, and for the supply of such rivers the surrounding continents must have possessed high mountain ranges, and must have been watered by a copious rainfall.

Again, although the area of deposition was constantly widened by subsidence, yet the detritus brought down from the higher to the lower levels was always sufficient to counterbalance this depression. Further, it would appear that all this material must have been obtained from the surface of the land, and transported by fluviatile agencies, for there could have been very little coast-erosion round the borders of this land-locked sea.[1] Rain and frost must therefore have been constantly at work on the surface of these continents, disintegrating and dislodging the rocks of which they were composed, while the rivers would be chiefly employed in carrying off the detritus so prepared, for the continued depression would have diminished their erosive capacity by lowering the slope of their channels.

It is a geological axiom that deposition is a measure of detrition, and we may see, therefore, in this enormous mass of sediments a measure of the detrition which took place, and of the amount of material removed from those portions of the great Carboniferous continent which drained into that sea whose limits have been indicated above.

Now the time necessary for the progress and consummation of all these natural operations must have been enormous, and yet the geographical changes must have been so slight and so slowly accomplished throughout this great length of time that they did not materially alter the relative positions of land and sea, or interrupt the process of swamp formation. This, then, is the peculiar and remarkable point in Carboniferous history which I desire to impress upon the reader's mind, that it was a period of internal quiescence, a period in which terrestrial disturbances were at a minimum, and consequently when the surface agencies of change were able to continue their course of action to a greater extent than usual. Now their course of action is such, that if they were allowed full play, and were not checked or balanced by uplifting movements, every continent would gradually be reduced in height, and worn down to a level but little above that of the sea, while the surrounding waters would be choked and shallowed by the materials poured into them from the wasting

[1] It is very probable that, as in the modern Mediterranean, the rise and fall of the tide in this sea was very small.

land. It would appear, therefore, that the Carboniferous was a period when this theoretical result was more nearly approached than it ever has been before or since ; when the continents were gradually lowered by the combined action of detrition and depression, the area of high ground being continually diminished, but the area of low-lying, swampy ground at or about the sea-level being continually increased, so that during the later part of the period similar physical conditions as to the climate, rainfall, surface slopes, soil, and vegetation seem to have prevailed throughout the greater part of the northern hemisphere.

The quiescent condition of the earth above mentioned and the slow rate of geographical change will account for the remarkable uniformity of life which prevailed throughout the Carboniferous period, a fact to which attention was called on p. 160. During the earlier portion of the period the changes consisted chiefly in an extension of the marine areas at the expense of the land, and we may suppose that after this subsidence the seas retained their same relative positions and connections throughout a long lapse of time, and that the denizens of these seas, spreading far and wide through the broadening water-spaces, found everywhere a similarity of conditions that enabled them to flourish and survive without change or variation. Later on, when the seas were shallowed by the continued deposition of material derived from the continents, and when the higher land was everywhere encircled by a wide belt of low-lying jungle and swampy ground, intersected by sluggish water-ways and lagoons, the conditions would be exactly those where nature would present a monotonous and uniform aspect, and where the plants and animals which had established themselves would be likely to maintain their existence unchanged so long as the same conditions prevailed.

In this way it seems possible to explain the widespread uniformity of Carboniferous deposits and the remarkable persistence of Carboniferous forms of life—phenomena which make this period a unique portion of geological time. It is as if we were contemplating the close of one great phase of the world's history, when the forces and causes which had hitherto been operative were exhausted and quiescent, when evolution was nearly at a standstill, and the world, or at any rate the northern hemisphere, was allowed a grand pause before entering on the mighty changes which were to commence a new order of things, and to give such a powerful impulse to the development and differentiation of the earth's inhabitants.

Recent researches have shown that these changes began before the close of the Carboniferous period, and though the first disturbances seem to have been local they built at least one range of hills, and are consequently of some importance. They were followed a little later by crust movements which affected the whole of Central and Southern Europe, and produced the mountain-chains which are known as the Armorican, Hercynian, and Variscan ranges.

In order that the reader may understand the manner in which these ranges of hills and mountains were developed and the order in which they came into existence, it is necessary to say a few words about the relations of our Coal-measures to those of the European Continent. French geologists divide the Carboniferous system into three series of beds, to which they have given the names Dinantian, Westphalian, and Stephanian, while in Russia the last two are represented by purely marine deposits, to which the names of Moscovian and Uralian have been given. Of these divisions the highest does not seem to exist in the British Isles, so that the Carboniferous succession found in the three countries may be correlated as follows :—

Britain.	France and Germany.	Russia.
Absent	Stephanian	Uralian.
Coal-measures and Millstone Grit	Westphalian	Moscovian.
Pendleside Beds and Lower Carboniferous series	Dinantian	Dinantian.

The production of the Armorican series of flexures and ridges seems to have taken place between the Westphalian and Stephanian epochs, and consequently after the deposition of our Upper Coal-measures ; but in England at any rate a crust movement took place before these measures were deposited, pressure from the east resulting in the formation of a mountain-chain, of which the existing Malvern and Abberley Hills are the worn-down remains. This chain has a general north and south direction, while the Armorican flexures run from east to west.

The ridging up of the Malvernian chain is a somewhat puzzling phenomenon for two reasons : the intense plication of its component rocks can only have been produced by very powerful movements, and yet they must have been rapidly accomplished ; again, it is difficult to understand the localisation of such powerful pressures within such a small area of the earth's crust, while the adjacent districts on the north and south of it were so slightly affected that in them the quiet deposition of Coal-measures seems to have continued without interruption.

Although the Malvern and Abberley Hills do not now rise to

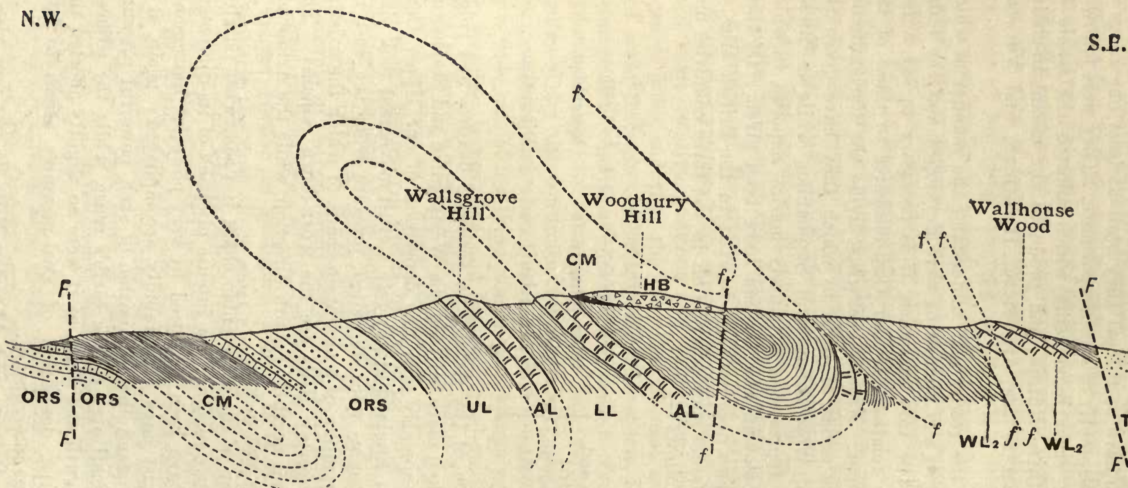


Fig. 25.—SECTION ACROSS PART OF THE ABBERLEY HILLS. Distance about 1½ miles. (By Prof. T. Groom.)
(Reproduced by permission of the Author and the Council of the Geological Society.)

Tr. Trias.
HB. Permian.
CM. Coal-measures.

ORS. Old Red Sandstone.
UL. Upper Ludlow.
AL. Aymestry Limestone.

LL. Lower Ludlow.
WL. Wenlock Limestone.
FF and *ff*. Faults.

any great elevation, only a little over 1100 feet in the Herefordshire Beacon, they possess all the structural characters of a mountain range which has been ridged up by great lateral pressure. The section (Fig. 25) drawn by Professor T. Groom illustrates the plication, overfolding, and faulting of the beds which form the northern end of the Abberley Hills, and shows how the older Coal-measures are involved in the overfolding, while the newer are not.

In the Malvern Hills still older rocks have been brought up to the surface, and the crushing has been much greater. The faulting and folding have been such as to bring up tracts or slices of Archæan and Cambrian rocks, and these have been crushed to such an extent that crush-breccias have been formed out of some of the harder beds, while the softer shales seem in places to have been entirely pinched out in the crushing in of the deep flexures. Professor Groom has described the structure of the hills, and more particularly of Raggedstone Hill, as follows:—

"There is then evidence to show that the gneissic rocks on the eastern side have been thrust up vertically, or at an angle, over the more westerly Cambrian and Silurian rocks. This hypothesis necessitates further the presence of folds sufficiently deep to bring the Palæozoic strata down to the level at which they are found. I have endeavoured to represent this view in the entirely diagrammatic figure (see Fig. 26, page 174). We must suppose that a deep fold of Cambrian and Silurian rocks, including, on the one hand, the Holybush conglomerate, and on the other beds of the May Hill series, became included in the gneissic complex, the middle limbs being drawn out by the great tension into a series of shreds, or in places entirely obliterated."

From this diagram, here reproduced by permission of the author and the Council of the Geological Society, it will be seen also how much broader the range must originally have been, for we cannot tell how far the flexures may be continued and repeated eastward beneath the cover of newer rocks. What remains of the range is only its western border, its eastern part having been subsequently thrown down by the great fault F^1, so that it is now buried at an unknown depth.

The northern extremity of this range of hills seems to have been near Wellington in Shropshire, and thence it extended southwards by Abberley, Malvern, and May Hill to Tortworth in Gloucestershire, possibly even still farther along the eastern side of the Bristol coalfield; but beyond this it cannot be traced, and if there was any farther prolongation it has been obliterated by the subsequent east and west folds of the Armorican ranges. The total length of this Malvernian chain is, therefore, less than 90 miles.

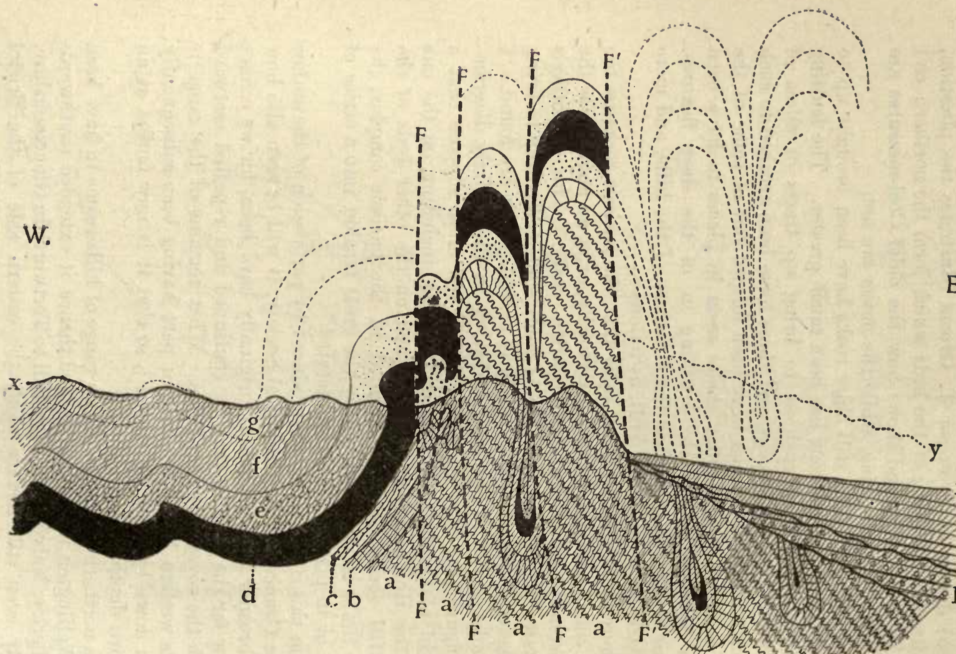


Fig. 26.—DIAGRAMMATIC INTERPRETATION OF THE STRUCTURE OF RAGGEDSTONE HILL, MALVERN. (By Prof. T. Groom.)

a. Archæan Rocks. *e, f, g*. Silurian Series. *h*. Permian Breccia. *y*. Pre-Permian surface.
FF. Faults. *b, c, d*. Cambrian Series. *i*. Trias. *xx*. Present surface.

But though the breadth of the area affected by the lateral pressures, as indicated by the length of the chain, was not great, the uplift in front of the range, *i.e.* on the eastern side of it, may have been sufficient to raise the whole breadth of the tract well above the sea-level of the time. Moreover, the vertical uplift may have been greatest in front of the Malvern Hills, so that the raised surface had a gentle northerly inclination. It is at any rate a fact that the Upper Coal-measures which were deposited on this ridge are thin, and belong more to the northern than the southern facies of that series.

The special characteristics of these two facies of Upper Coal-measures must now be pointed out. The type of the northern facies is found in North Staffordshire; here its thickness is about 2500 feet, and there is no break between it and the Middle group. It consists chiefly of red and purple marls and shales, with bands of grey and purple sandstone, some thin coal-seams, and thin beds of limestone. In South Staffordshire this series overlaps the Middle group on to the Cambrian and Silurian rocks near Rubery. In Shropshire there is marked unconformity between the Middle and Upper Coal-measures, the former having been flexured and planed off before the deposition of the latter, which pass over them so as to rest directly on the Old Red Sandstone.

Passing now to the southern area this series is represented by groups known as the Pennant series and Upper Coal-measures, but their lithological aspect is very different. The Pennant Beds are mainly massive grey micaceous sandstones, but include some shales and thin coal-seams. The higher measures exhibit the more usual alternations of shales, sandstones, fireclays, and workable coal-seams; the sandstones in the lower part being like those of the Pennant group, and beds of a purple colour only appearing in the very highest measures. The total thickness is greater than in Staffordshire, being about 3500 feet in Somerset, while in Glamorgan it increases westward from 3000 to over 4000 feet.

The small coalfield of Dean Forest includes Pennant sandstones of the same type, but the higher beds have been removed by subsequent detrition. Near Newent, however, only 5 miles to the N.E., there are Coal-measures resting on Lower Old Red Sandstone, and apparently belonging to the northern facies.

Recurring to this northern facies, its peculiarities require some further notice; the prevalence of red, purple, and green colours, and the occurrence of mottled red and green clays are so remarkable that they caused the earlier geologists to class the beds as Permian, and in fact it is only quite recently that the highest group (Keele Beds) has been separated from the Permian and recognised as Carboniferous. Again, the thin beds of limestone which occur are not made up of organic remains, but are generally compact and earthy, though they often contain Entomostraca, and the minute annelid called *Spirorbis*. No essentially marine fossils have been found in any part of the series.

Red and mottled clays occur in other formations under conditions which show them to be lacustrine deposits. The colouring matter of the sandstones is ferric oxide, every grain being coated with a thin pellicle of such oxide, as if the colouring matter had been deposited upon every grain as it came to rest at the bottom of a stagnant body of water. Now such an amount of iron oxide is not likely to accumulate in waters which opened into the sea, but might do so in lakes and swampy tracts which were not traversed by any strong currents, and were never invaded by the sea-waters.

Professor Green, indeed, thinks that these beds were formed in lakes which had no outlet at all, and the waters of which were gradually concentrated by evaporation. He points to the limestones as having characters which resemble those of limestones formed by precipitation from saturated solutions, and such saturation is certainly almost an impossibility in a lake with an outlet.

The geographical distribution of the beds of this type also supports such an explanation. They occur in all the Midland coalfields, as well as in those of Denbighshire, Lancashire, Yorkshire, and Cumberland. They occur also in Scotland near Canonbie, and probably also in the western basins. Though they have not been found in Ireland, it is quite possible that they may have existed in the northern part of that country, and have been removed by subsequent denudation. The fact remains that these red measures are restricted to the region which lies to the north of the Midland ridge.

A reference to the map (Fig. 23) will show that this area is just that which is most likely to have been isolated and converted into a shallow lake or group of lakes by a slight geographical change. As already mentioned, it is probable that the Malvernian movement raised a broad tract of dry land across Central and Eastern England, and this was doubtless united to the continental land to the east of the British area. When subsidence and deposition were renewed it would take some time for this tract to be completely submerged, if indeed it ever was reduced to that condition. Again, it is by no means unlikely that a similar land-bridge was at the same time formed in Ireland between

Galway and Kildare, for it is a fact that all the chief coalfields of Ireland lie to the south of the central limestone area, and that no Coal-measures of any kind occur along the line indicated, the nearest being a small patch near Kiltamagh in Mayo, which is mapped as lying directly on Carboniferous Limestone.

However it may have been accomplished, the characters of the northern Upper Coal-measures and the absence of marine fossils make it highly probable that the area in which they were formed was isolated from those on the south, and was converted into a lacustrine basin or series of such basins. Such seems to have been the last stage in the geography of the Carboniferous period so far as British deposits are concerned. The final uplift of the region will be discussed in the next chapter.

CHAPTER VIII

THE URALO-PERMIAN PERIOD

It was stated on p. 171 that the deposition of the Westphalian series, to which all our British Coal-measures belong, was followed by an epoch of great tectonic importance, during which a considerable tract of European ground was ridged up into a mountain range by pressures acting from the south, which produced a long series of east and west flexures. These have been termed the Armorican folds by Professor Suess.

The whole of Western and Central Europe seems to have been raised to form part of a great continent, and the sea retreated eastward into Russian territory. It is therefore in Russia that we find the most complete and continuous series of marine deposits connecting those of Carboniferous age with those of later date (Permian), and these intermediate deposits have been called the Uralian series. In France and Central Europe they are represented by the Stephanian Coal-measures, but no such measures have yet been found in England.

By its flora and fauna the Stephanian series may properly belong to the Carboniferous system, but from a tectonic and orogenetic point of view, it is much more closely linked to the Permian group; and as the British records of this time consist only of a series of Armorican flexures and of some Permian deposits, I shall combine in this chapter an account of the Armorican ridges and ranges with a description of the subsequent events in Permian times. In other words, I shall be dealing with what may be called the Uralo-Permian period.

1. *The Armorican Flexures*

The importance of the Armorican folds has long been recognised, and was first pointed out by Godwin-Austen in 1856,[1] though he

[1] *Quart. Journ. Geol. Soc.* vol. xii. p. 38.

did not give them a name. They are important not only because they have played a prominent part in the building up of the European continent, but also because the productive Coal-measures are involved in the folding, and consequently the present position of coalfields within the Armorican area of influence is determined by these lines of flexure.

The northern border of the Armorican range emerges from the Atlantic Ocean in the south-west of Ireland, and some mention of its component flexures has already been made in Chapter VI. (p. 111). The physical features of the district are indeed so entirely the result of these folds that their direction can be seen on any ordinary map of Ireland, for the anticlines of hard Glengariff Beds run out as long promontories into the Atlantic, while the softer beds brought in by the synclines have been eaten out by the Atlantic waves, and now form long parallel inlets.

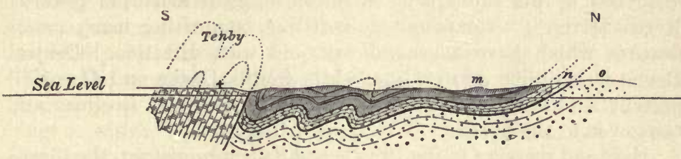


Fig. 27.—SECTION ACROSS THE PEMBROKESHIRE COALFIELD.

m. Coal-measures. *n.* Carboniferous Limestone. *o.* Old Red Sandstone.

One of these anticlinal ridges rises into the highest hill-range in Ireland, that of Macgillycuddy's Reeks, with a peak of 3414 feet above the sea. The axes of the folds run to the E.N.E. in Kerry and West Cork, but are deflected into a nearly due west direction in Waterford, where they meet and displace the Caledonian foldings. The folds are fairly regular, sometimes bent over toward the north, and at least in one case (near Killarney) an anticline is overfolded, so that Carboniferous strata are pinched in below those of Devonian age.

The continuation of these folds is found in Pembrokeshire, where again they displace and truncate the Caledonian folding, and are again marked by overthrust and faulting, as shown in Fig. 27. Thence they are continued through Glamorgan, and by their interference with the older Caledonian folding they have produced the periclinal dome of Usk, and the curiously shaped syncline of the Chepstow and Dean Forest area.

On the eastern side of the Bristol Channel they meet the previously formed Malvernian range nearly at right angles, and the result is the complicated arrangement of folds and faults which is found near Bristol and Radstock. The displacements in the syncline are so extraordinary that the relative positions of the strata in some places have not yet been satisfactorily explained, but there is certainly overfolding or overthrust faulting. South of this lies the anticline of the Mendip range, and reference to any geological map will show that this is part of a curved ridge which presents a concavity to the north, *i.e.* toward the truncated end of the Malvernian range. Moreover, it is in the centre of this curve, near Downhead, that the oldest rocks in the Mendip arch come to the surface, as they would be likely to do if the Armorican fold was here overriding an older Malvernian fold.

The eastward continuation of the Armorican flexures is concealed by the Mesozoic strata beneath which they pass, but a similar parallel series of folds is found to the south throughout the Palæozoic area of Devon and Cornwall, except where they are disturbed by the subsequent intrusion of great masses of granite. North Devon is a compound ge-anticline, comprising many minor flexures which have a general east and west direction. Central Devon is a similar geosyncline, while South Devon and Cornwall present a succession of flexures which are generally isoclinal and bent over to the north.

Here and there, as in the Prawle and Salcombe district, the Lizard and the Eddystone rock, the vertical uplift of the anticlines has been great enough to bring up small tracts of the Archæan rocks, which form the very foundations of the country. On this point Professor Bonney has made some suggestive remarks, which are quoted in the following paragraphs :—

"I can hardly understand the production of those great parallel flexures which affect all south-western England . . . without assuming the existence to the south of them of a great axial mass of much harder rock, to the pressure of which these crumplings are due. On comparing a section of South Devon with a series of sections across the Alps we cannot fail to be struck with the resemblance between them, except that in the former we do not find the crystalline nucleus rising up as the central mass of the chain, often overtopping and apparently overlying the later deposits. But when we look to the south, beyond the South Devon and South Cornish schists, we find at the Eddystone—we find yet farther south in the Channel Islands and on the adjoining coast of France—large masses projecting from the ocean of much more coarsely crystalline rock."

"Is it possible that these may be the foundation-stones of a great mountain region, of whose outer zone South Devon and South Cornwall are the last remnants,—the relics of a long-vanished highland region of Archæan rock? If so, the mountain-making . . . was one of the closing incidents of the Palæozoic volume of geological history. Yet the Channel Sea now occupies the place where this range was upraised, and of its ruins some fragments only remain *in situ*. These remarks may seem to belong rather to the poetry than to the prose of Science; but I think that any one who will spend a few years in studying the structure of rocks and of mountain-masses will see that the idea conveyed by them is something more than a baseless flight of imagination." [1]

The question above asked by Dr. Bonney was answered in the affirmative by Professor Suess the following year (1885), when he agreed with the views expressed by Dr. Bonney, and remarked: "What we see here is the ruins of a mighty mass of lofty mountains" (*Face of the Earth*, Eng. trans. vol. ii. p. 89).

The structure of Brittany and the west of Normandy has already been briefly indicated in Chapter III. This is the typical Armorican region, and has been described by many writers, but especially by Professor C. Barrois in many maps and memoirs. The colours which indicate the Archæan and Palæozoic rocks on a geological map of Brittany appear as a series of bands, varying in width, but having a general E. and W. direction, with a tendency to converge westward. These bands are produced by a series of flexures like those of Devon and Cornwall. The detrition and planation of the country during subsequent periods has led to the destruction and removal of the rocks which formed the upward prolongations of the anticlinal arches; so that the original hill-ranges have been razed to their foundations, and it is only in the synclinal troughs that the newer Palæozoic rocks have been preserved.

M. Lecornu,[2] moreover, has shown that the westerly convergence of the flexures is only part of a general divergence round an area or core of special resistance. Thus in Normandy the lines of flexure curve round so as to run from N.W. to S.E., as if they had been forced out of their normal course by the resistance of some hard rock-mass to the south of them.

M. Bigot has completed the demonstration of this resistant mass or core of rock, and the map (Fig. 28) has been adapted from that which accompanies his Memoir on the "Structure of Basse Normandie." [3] In explanation of this I translate the following remarks: "The map shows that this change in the direction of the folds corresponds with their position in regard to one

[1] *Quart. Journ. Geol. Soc.* vol. xl. p. 25 (1884).
[2] *Bull. Serv. Cart. géol. France*, No. 33, t. iv. p. 395 (1892).
[3] *Bull. Soc. Géol. de France*, S. 4, tom. iv. p. 881 (1907).

of the cores to which M. Lecornu has attributed the deviation of the folds in the Cotentin. The limit of the Cambrian strata is shown on the map, and I have previously mentioned that inside the area thus limited the Ordovician rests directly on the pre-Cambrian. It is, therefore, a land-mass of ancient consolidation—an ancient dome of uplift, raised during Cambrian time, which has played the part of a resistant core in respect to the thrusts which have flexured the Armorican region. Under the influence of the thrust the synclinal waves have been bent over in different directions on each side of this obstacle. On the north side the folds slope towards the south ; on the south side they are inclined to the north."

Moreover, there are many strike-faults parallel to the direction of the folds, and their hade has a definite relation to the pitch of the isoclines and to the position of the central *core-massif* ; for the faults in Normandy are all downthrows to the north, while the long fault on the south side of the core, parallel to the anticline of Rennes, is a downthrow to the south. Possibly the faulting was later than the folding, for it looks as if the rocks had fallen away from the central core.

From the descriptions above given it will be seen that a considerable tract of the earth's crust, extending from Bristol on the north to La Vendée on the south, a distance of about 330 miles, has been crumpled into a succession of parallel folds simple and compound, some narrow and some broad, but all having the same general east and west direction. The tract is, in fact, part of a set of worn-down mountain ranges, and if we may judge of the relative height of the ridges by the age of the rocks which are exposed in them, it would seem that the highest ranges lay along the northern parts of Brittany and Normandy, where the broadest strips of Archæan rocks are now found.

Both in England and France the eastern portion of the Armorican ranges passes below the newer rocks which fill the great depression of the Anglo-Parisian basin. With the subterranean course of the southern Armorican ridges we need not concern ourselves, but the continuation of the more northern flexures below the south of England and across the Straits of Calais to the Boulonnais is of essential importance to a proper comprehension of the subterranean geology of that area.

It might seem hazardous to assume that the western flexures were continued beneath the south of England were it not that a close correspondence has been proved to exist between these flexures and those of much later date which affect the Cretaceous and Eocene Beds. The coincidence of the Armorican with the

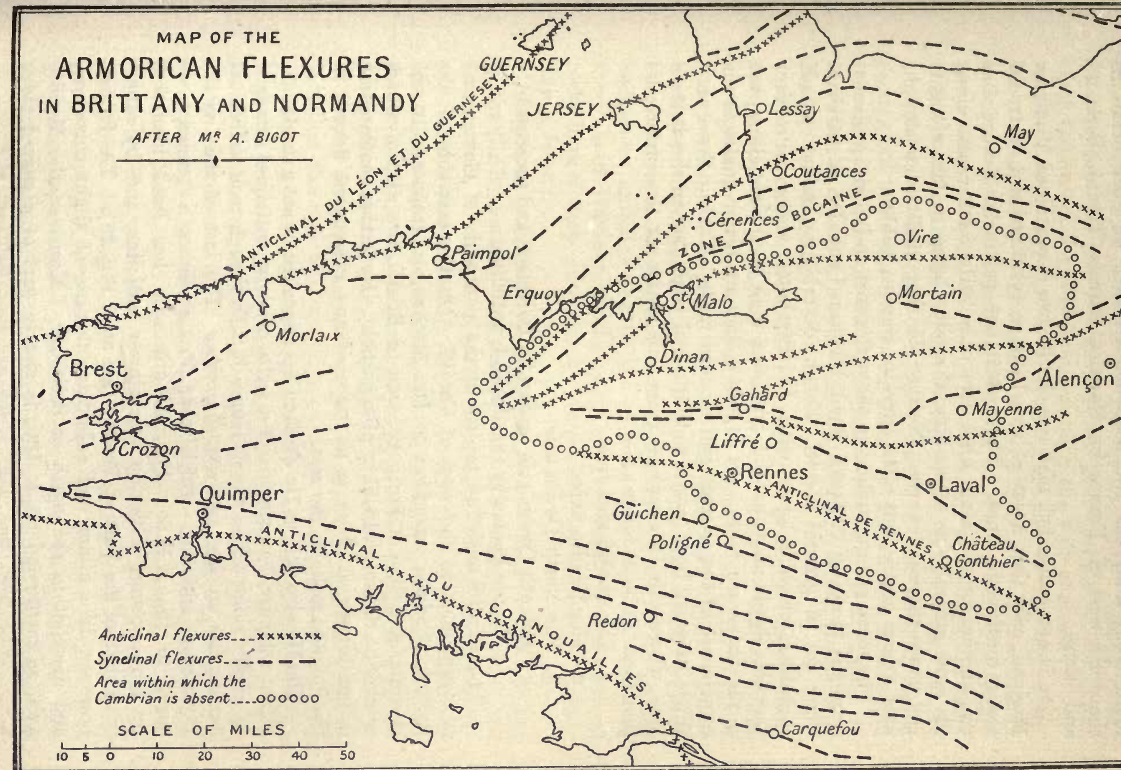


Fig. 28.—MAP OF THE ARMORICAN FLEXURES IN BRITTANY AND NORMANDY.

more recent folds has also been demonstrated in much detail in the north-west of France by Gosselet, Barrois, Parent, Bertrand and others.

It is not contended that any one flexure is continued all across England, only that a set of anticlines or synclines can be traced along continuous lines. Thus when one particular flexure dies out, another of the same kind sets in a little farther east along the same general line of country, the folds being in fact elongate and canoe-shaped flexures. Neither do they maintain a straight west to east course, but often curve in sinuous fashion.

The most recent studies of these flexures and their prolongations are those by Professor Boyd Dawkins[1] and Dr. A. Strahan. They are in general accord, though differing on minor points, regarding which I agree with Dr. Strahan's views. Professor Dawkins dwelt more on the synclines than on the anticlines, but as the latter are more easy to follow they are better guides to the coincidence of the ancient and modern folds. Taking these anticlines in order from north to south, and beginning in the western area, where the Palæozoic flexures are visible at the surface, we find them to be as follows :—

1. The Cardiff anticline.
2. The Mendip axis.
3. The North Devon axis.
4. A South Devon axis, broken by Dartmoor, and consequently better known as the Purbeck anticline.

The Cardiff anticline begins in the peninsula of Gower, and is conspicuous to the west of Cardiff. On the east side of the Bristol Channel, according to Dr. Strahan, it reappears in the irregular anticline of Portbury, west of Bristol, the axis of which crosses the Bristol coalfield by Mangotsfield. Its further continuation is not known, as there is no trace of any subsequent flexure in the Neozoic rocks to the east.

The Mendip axis, as Dr. Strahan has remarked, is not a single continuous flexure, but consists of a series of short anticlines arranged *en échelòn* along a line which ranges E.S.E., though each individual flexure has an east and west direction. The last of these is the Downhead anticline, which near Frome shows a tendency to curve to the E.N.E. The Mendip axis has been identified by some authors with the Warminster anticline, and by others with that of the Vale of Pewsey (see map, Fig. 29). The former, however, is a minor and subsidiary flexure, of slight curvature, and dies out to the north of Salisbury. Moreover, the Mendip axis, as mentioned on p. 180, is clearly part of a curved ridge

[1] See *Geol. Mag.*, 1894, p. 459, and *Proc. Fed. Inst. M.E.*

bent southward by interference with the Malvernian range; hence its true continuation is found in the prolongation of the curve along the foot of the Wiltshire Downs to the Vale of Pewsey.

The Pewsey anticline is of Tertiary age and of varying curvature, being rather a succession of periclines than a continuous anticline. It can be traced eastward to the Vale of Shalbourn, and is then deflected to the E.S.E. through the Kingsclere dome to the northern border of the Weald, where it runs eastward for a considerable distance, but again bends to the S.E. in Kent, passing out below the Straits of Dover at Hythe, and pointing to the northern part of the Boulonnais, where a small patch of Devonian and Carboniferous rocks actually rises to the surface near Ferques (see Fig. 29).

The second or North Devon axis is really a complex and compound one, including several sets of flexures, and so being more properly termed a ge-anticline. It forms the broad ridge of Exmoor and the isolated block of the Quantock Hills; east of these the ridge has been planed down by the waves of Mesozoic lakes and seas, but the axis is still marked in the Trias by the Sedgemoor anticline and by the still more pronounced flexure of the Vale of Wardour, on the north side of which the Cretaceous rocks have a steep pitch to the north and are broken by a long line of fault.

The same ge-anticline is continued by a series of smaller domes in the Chalk country by Salisbury and Winchester, and from the latter place it curves S.E. by the Meon Valley to Petersfield, and then swerves slightly to the north of east, and must be identified with the central axes of the Wealden area, not with the minor anticline of the South Downs, as Dr. Barrois thought in 1875 (*Recherches sur Terr. Crét. Sup.* p. 120).

Topley long ago pointed out that there is no single continuous anticline through the central area of the Weald, but several sets of more or less replacive anticlines. The Petersfield anticline seems to be prolonged by Harting, Combe, Lynch, and Lurgershall to Horsham, where as a distinct flexure it dies out. Another begins, however, a little way to the E.N.E., and passes through Crowborough by Ticehurst, Hawkhurst, and Wittersham to Romney Marsh, and under the sea near Dungeness. Another anticline is found near Cuckfield, to the S.E. of Horsham, but cannot be traced very far, and is probably of an elongate canoe-shape. If, however, the line of its axis is continued, it reappears near Buxted on the river Ouse, and brings up the Purbeck Beds to the north of Heathfield and Battle, passing thence to the coast north of Hastings (see Fig. 29).

Fig. 29.—GEOLOGICAL MAP OF THE SOUTH OF ENGLAND, SHOWING

The third main Armorican axis begins in the north of Cornwall and runs a little north of Launceston to Lydford, but its continuation through Devon has been broken by the subsequent intrusion of the Dartmoor Granite. East of this mass it probably passes below the Haldon Hills and under the sea near Exmouth. Near Weymouth and in the Isle of Purbeck it appears as a strongly marked series of anticlines and faults, which are continued eastward through the southern part of the Isle of Wight.

Let us now see whether the continuations of the Wealden flexures can be identified with those in the north-east of France. It was for a long time thought that the Mendip anticline was the same as the well-known axis of Artois in France and Belgium, but Bertrand has shown that the axis of Artois does not pass along the northern side of the Boulonnais through Ferques, but enters the S.E. corner of that area and passes out near Boulogne. By use of mining records and careful plotting of the subterranean contours of the Palæozoic rocks beneath the Cretaceous cover, Bertrand has also shown that the northern axis of Ferques can be traced south-eastward to Réberques, and then it curves eastward toward St. Omer. It is this axis which is the continuation of our Mendip and North Down line, while the axis of Artois is repre-

THE ANTICLINAL AXES OF THE ARMORICAN FLEXURES.

sented by the main Crowborough axis of the Weald and by the North Devon ridge (see map, Fig. 29).

Lastly, M. Bertrand's plotting of the subterranean contours shows the existence of a dome between Fruges and Pimont, and the axis of this, if continued, would pass to the north of Etaples, and may be on the same subsidiary line of flexure as the Battle and Cuckfield anticlines in Sussex.

The smaller flexures which are connected with the line of the South Downs probably die out in the Channel, but the Purbeck axis, being a much stronger flexure, is probably continued under the Channel and may be represented in France by the "axis de la Bresle," which cuts the coast near Trèport, and there has a N.W. to S.E. strike.

I agree with Bertrand in thinking that the axis of Bray, which is a very strong and important flexure in the north of France, passing out to sea at Dieppe, most probably curves westward, like all the other axes, and passes down the centre of the English Channel. It is even possible that its continuation may be found in the faulted uplift of the Archæan in South Devon, but this must be regarded as merely a suggestion, because of the great extent of sea-space between them.

I have described the flexures which traverse the south of

England in some detail, because they indicate the course of the subterranean Armorican ridges, and it is by a careful consideration of these axes that we gain a clue to the probable position of the corresponding synclines, in which coalfields probably occur beneath the cover of the newer deposits. One such coalfield has already been found in the south-east of Kent, and others may hereafter be discovered on the north side of the Mendip-Pewsey anticline in Surrey, Berkshire, and Wiltshire.

Before leaving the subject of the Armorican range it should be mentioned that the mountain-building of this epoch did not stop at the axis of Artois and the ridge of the Ardennes, but was continued eastward in the Variscan range, which extended through Central Europe by the mountains of the Rhine, the Taunus range, the Black Forest, the Hartz, the Erzgebirge, the Frankenwald, and the Thuringenwald. The connection of all these ranges has been described by Professor Suess,[1] who believes that the highest summits of the ancient Hercynian Mountains rose above the Ballons des Vosges, the south part of the Black Forest, and the Erzgebirge.

There can be little doubt, from the abrupt manner in which the Armorican flexures terminate along the Atlantic seaboard from Ireland to Spain, that the continent included a large part of the North Atlantic region, and some geologists, such as Bertrand and De Lapparent, have not hesitated to include the whole of this region with a large part of North America in the same continent.

As mentioned on p. 178, the crust-movements which produced the Armorican and Hercynian ranges of mountains were succeeded by an episode or quiet interval, the record of which is found in the Stephanian Coal-measures of Central France and the Ottweiler Beds of the Sarre district. We must suppose that the greater part of Central and Western Europe had been raised into dry land and united to that of the previous Carboniferous time ; so that deposition could only be continued in the lakes and lagoons which occupied the deeper depressions of the corrugated surface.

It is quite possible that some such restricted areas of deposition existed at this time on British ground, but if so they seem to have been destroyed by the long-continued erosions of Permian and Triassic times. The probability of the former existence of such basins is indicated by the fact that a patch of Stephanian Beds occurs at Littry in Normandy, where they are conformably succeeded by beds of Permian age ; again they occur farther south in the basin of Laval (Mayenne), where Stephanian Coal-measures with a conglomeratic base lie unconformably on overfolded Westphalian Beds.

[1] *The Face of the Earth*, Eng. trans. vol. ii. p. 97.

2. *The Lancastrian and Pennine Flexures*

In the north of England there are other lines of faulting and folding which differ in direction from the Armorican, and still more widely from one another in that respect. One set of these runs from S.W. to N.E., with sometimes a deflection to the E.N.E.; its strike is thus coincident with that of the older Caledonian folding, but it is clearly of post-Carboniferous age, and may be of Armorican date. The other set of folds are those of the Pennine range, which have a general N. to S. direction, with a deflection to the S.S.E.; with these I associate the later Charnian flexures in Leicestershire. There is no absolute proof that the Pennine flexures are later than the other set, but there is reason to think they are, and I shall therefore describe them after those first mentioned. It is unquestionably to the intersection of these two sets of flexures that the conformation of our northern coal-fields is mainly due, and that they have the shape of basins.

A. The Lancastrian Flexures.—As the first-mentioned set of flexures are most conspicuous in Lancashire I shall term them *Lancastrian.* The coincident relation between their axis and those of the Caledonian folds is probably one of cause and effect, for the older lines would be those of least resistance, and the rocks would give way along them under later stresses; just as in the south of England the Tertiary flexures follow the main axes of the older Armorican folds. Consequently, it is very likely that the Lancastrian flexures were contemporaneous with the Armorican, in spite of there being a little difference in their trend.

Beginning on the north side of the Lake District we find on its N.W. border a fault of some magnitude displacing the Carboniferous rocks through a vertical distance of 1200 feet, but passing under five outlying patches of Permian Beds without affecting them. Moreover, these Permian outliers pass across the fault from Coal-measures on to Carboniferous Limestone; near Egremont a band of Permian lies on the lowest beds of this limestone, and near Gosforth a thin band of the same rock emerges from below the Trias and rests directly on the Ordovician Borrowdale series. Lastly, on the other side of the Lake District, in the Eden valley, the local Permian breccias are largely made up of fragments of Carboniferous Limestone.

From these facts it is clear that the central axis of the Lake District had been raised into a broad anticlinal swell, which probably included the Isle of Man,[1] and had a direction from

[1] On this point see G. W. Lamplugh in *Quart. Journ. Geol. Soc.* vol. lvi. p. 22.

S.W. to N.E. From the higher parts of this broad arch an immense amount of rock material must have been removed before the Permian sandstones were deposited over it. It may be assumed that the average thickness of the Carboniferous strata which covered the older Palæozoic rocks amounted to at least 4000 feet, and was made up as follows:—

Coal-measures	2000 feet
Millstone Grit	800 ,,
Carboniferous Limestone . . .	1200 ,, (or more)

The removal of so much material must have occupied a long period of time, for we must remember that the whole area had been in the condition of a silted-up Coal-measure swamp, and that when it was raised into dry land it had not to pass through the destructive surface of an open sea; hence its denudation must have been accomplished by the gradual processes of subaerial erosion and detrition. It is evident also that on the western side of the district these agencies had removed not only the whole Carboniferous cover, but had eaten some way into the underlying Ordovician rocks. So great an amount of erosion suggests that it occupied the whole of Stephanian time, and confirms the view that the flexuring was of Armorican date.

I am, therefore, in agreement with Dr. Strahan, who has expressed his opinion "that it was in consequence of the pre-Permian movements that the older rocks of the Lake District were freed from their Carboniferous covering, and that to this extent the district may be said to have been blocked out in pre-Permian times,"[1] though all the existing physical features of the ground date from a much later period.

South of the Lake District is the broad area of the Lancaster Moors, which is a syncline striking in the same direction and extending N.E. to Bentham and the Ingleton coalfield, on which lies an outlier of Permian sandstone, the whole being cut off abruptly by a post-Permian fault. The average width of the tract of Millstone Grit in this syncline is 14 miles.

Parallel to the above is the Pendle anticline, having an average width of about 10 miles and traceable for a distance of 40 miles, from Pateley Bridge on the N.E. to where it is cut off by a cross-fault running from Garstang to Mellor (near Preston). It is really a compound anticline, having two main anticlinal axes, and its age is proved by the occurrence of a Permian outlier resting on Carboniferous Limestone near Clitheroe.

Still farther south is the Todmorden anticline, which brings

[1] "Address to Section C. of Brit. Assoc.," and *Geol. Mag.*, 1904, p. 454.

up Carboniferous Limestone between that town and Heptonstall, and is prolonged north eastward through Keighley, and reappears at Harrogate in Yorkshire. It is doubtless also responsible for the general S.W. and N.E. trend of the Lancashire coalfield, and for the appearance of the large inliers of Millstone Grit which are found in the central parts of that coalfield.

The breadth and low curvature of these northern flexures clearly indicate that the compressive force which formed them was much less intense than it was in the south of England, and they may be regarded as the marginal ripples or undulations of the more violent Armorican disturbances. It is probable that the region affected by them, which was probably the whole of Northern England, was not raised to any great height above the sea-level at the time of their incidence, but they are none the less important as part of the tectonic Armorican episode.

B. The Pennine Flexures.—The Pennine range has been called the "Backbone of England," and though sometimes limited to the hills which separate the coalfields of Yorkshire and Notts from those of Lancashire, Cheshire, and North Staffordshire, it is really applicable to the whole northern range of uplands which form the watershed between the eastern and western river-basins.

The question whether this Pennine range as a whole came into existence before the deposition of the Permian Beds, which lie on each side of it, is one which has been much debated. Professor Hull, writing in 1869, found reason to think that the uplift of the range was post-Permian and pre-Triassic, but subsequent writers differed from this view,[1] alleging the following reasons :—

1. The flexures of the South Yorkshire and Derby coalfields are certainly pre-Permian, and as their major axes are parallel to the central Pennine axis, it is probable that the latter was formed at the same time.

2. No outliers occur at any distance west of the main Permian escarpment, and no fragments of Magnesian Limestone have been found in the Triassic rocks, as might have been expected if that limestone had passed over the Pennine axis, and had been subjected to erosion in Triassic times.

3. On the other hand, fragments of Carboniferous Limestone have been found both in the Permian breccias and the Triassic sandstones, which would prove that this limestone had already been bared along the Pennine axis.

4. If the Permian rocks on each side of the range had been

[1] Wilson, in *Geol. Mag.*, 1879, p. 500 ; and Teall, *Geol. Mag.*, 1880, p. 349.

originally continuous they would have been lithologically similar and correlative. Whereas they are so dissimilar that they are regarded as two distinct facies, limestones prevailing in the eastern and red sandstones in the western.

5. Though the general direction of the Pennine axis is from north to south, it becomes deflected toward the S.S.E. on its southern border near Ashbourne and Derby, where it passes beneath the Triassic plain. When Carboniferous rocks emerge again in Leicestershire with the same S.S.E. strike, there is evidence that the folds and faults are of pre-Permian age.

The proofs of the last statement were brought forward by Dr. H. T. Brown in 1889,[1] and his remarks are worth quoting. "That the age of these movements is in the main post-Carboniferous is beyond doubt, for we find both the older Palæozoics and the Carboniferous rocks equally affected by them ; but whilst in the Nuneaton-Charnwood area we have nothing, so far as I know, which fixes more definitely the age of these flexures, we have, on the other hand, a valuable chronological index in the thin Permian beds of the Leicestershire coalfield ; for the non-participation of these strata in the general folding of the older rocks, and the undisturbed way in which they lie, bridging over the great N.N.W. and S.S.E. faults, proves the age of the disturbances to be pre-Permian." On a previous page he had mentioned that the Boothorpe fault displaces the Coal-measures to the extent of at least 1000 feet, but only affects the Permian and Trias to the amount of 20 or 30.

The reasons above given are sufficient to prove that the original uplift of the Pennine range was pre-Permian, and not of a date between Permian and Triassic time. This uplift, however, was not great, and the ridge produced not of great elevation, for, as we shall see, the Trias probably passed over it. The broad anticlinal curvature of the whole region was clearly produced at a much later date, because both the Trias and Lias are affected by it.

3. *The Cornubian Uplift*

There is yet another area where great physical and geographical changes took place in the interval between the Carboniferous period and the formation of local Permian deposits. This is in the south-west, and includes Devon, Cornwall, and the adjacent parts of the English Channel. The disturbances in this area are apparently connected with the intrusion of the great masses of granite which break through all the older rocks, including the

[1] *Quart. Journ. Geol. Soc.* vol. xlv. pp. 9 and 33.

Carboniferous, and also interfere with the strike of the Armorican flexures, so that the intrusions are of post-Armorican date.

The most northern of these granitic areas is that of Dartmoor, and there are four other large tracts of similar granite, the last being that of the Penzance and Land's End district. The Scilly Isles are the remains of a sixth tract, and there may have been others still farther to the south-west.

It is very probable, as the late R. N. Worth suggested in 1889,[1] that these granitic masses formed subterranean reservoirs which were connected with volcanic rocks at the surface. It seems, however, to be the general opinion that he carried his theory too far in imagining the Dartmoor granite to represent the core of a single gigantic volcano ; it is much more likely that the granite mass cooled and partially consolidated under a considerable cover of Devonian and Carboniferous rocks, and that its connection with the surface was by means of fissures and dykes, above which several or even many volcanoes of moderate size were established.

In this matter I agree with Mr. A. W. Clayden, who has discussed the subject at some length in a recent book.[2] He remarks: "It is more likely that each granite mass represents the base of a district which was thickly dotted over with ruined cones of intermediate composition, and smaller craters and hills built up from the later rhyolites,[3] volcanic glasses, and beds of ash. As long as the vents remained open the cooled parts in the upper portion of the reservoir would be drawn off from time to time, and the molten mass would remain hot enough to go on dissolving the over-lying solid crust." . . .

"If we suppose the dome of molten material to have been originally covered by Devonian rocks as well as Culm, and that these were largely mixed with, or covered by, the earlier intermediate extrusions, this process of solution would bring the granite through each in turn until it attained to a level so near the surface that the rate of cooling exceeded any possible gains of temperature from below." But, as he points out, the cooling would not be an uninterrupted process ; minor disturbances would occur, cracks would be formed, and fluid material from beneath would be injected into them. "Hence the elvans or granitic veins which are found in great numbers penetrating not only the surrounding sedimentary rocks, but even the granite itself, or at least its marginal parts." It may be added that differential

[1] See *Geol. Mag.* for 1894, p. 97.

[2] *The History of Devonshire Scenery* (1906), p. 80.

[3] By the word "later" he means later than the Carboniferous basic lavas which may have proceeded from the same reservoirs.

strains would be set up, earthquakes would occur, fresh fault-planes be formed, and minor volcanoes would come into existence on the flanks of the greater volcanic region.

The real existence of such volcanoes is attested by the lava flows which lie at the base of the Permian series near Exeter, these rocks ranging in composition from trachytes to basalts, and including some mica-trap or lamprophyre. Moreover, the overlying Permian breccias contain blocks of quartz-porphyry, rhyolite, and andesite in abundance, proving that flows of such lavas were then exposed to erosion and disintegration. Dykes of lamprophyre, gabbro, and at least one of quartz-porphyry are known to occur on the western side of Dartmoor, and quite recently dykes of mica-trap have been found in the Camel valley, as well as near Newquay and Falmouth, all of them being probably of the same age.

Neither are signs of the earthquakes wanting, for around Brixham and at other places in South Devon irregular fissures may be seen filled with red calcareous sandstone. These are conspicuous in the limestone cliffs of Berry Head, where they can be seen running from top to bottom. I have little doubt that they are earthquake fissures formed during the period of volcanic disturbance, and filled with the red sand of the early Permian deposits, cemented into a sandstone by the subsequent infiltration of calcite.

The intrusion of these granitic masses, and the extrusion of lavas from the volcanoes by which Dartmoor and probably most of the other masses were crowned, evidently created a chain of mountains which had a general N.E. and S.W. direction. Crossing the Armorican flexures obliquely, it obscured and partially obliterated them, at any rate so far as surface features were concerned.

Moreover, there seems to have been a contemporaneous or subsequent subsidence of an extensive area to the S.E. of this volcanic region, for, as we shall presently see, a large part of the adjacent area now occupied by the English Channel and the east of Devonshire became a basin of deposition which persisted throughout the Permian and Triassic periods. Rock-fragments belonging to both these series have been dredged at many spots between the Eddystone and a point some 12 miles S.E. of the Lizard. Post-Carboniferous granites also occur in Brittany, and the area of greatest subsidence may have lain in a space between two converging lines of volcanoes.

It is well known that local subsidence has often occurred as a sequel of volcanic action, sometimes including the actual area of vulcanicity, sometimes affecting an adjacent area, especially in regions where earthquakes are frequent. It may be supposed that the area subsides either in consequence of the removal of much molten matter from beneath it, or as a consequence of the cooling and resulting contraction of such molten material.

However the subsidence was caused, it is clear that in early Permian time a large area, across which Armorican ridges had previously extended, did gradually subside so as to become an enclosed basin-shaped depression. It may be compared with that of Lake Seistan in the S.E. of Persia, which lies in a volcanic district, and is believed to be an area of subsidence; the basin of this lake is about 130 miles long with a maximum of 60 in width.

4. *Permian Deposits*

The long period of time which is represented by the succession of terrestrial disturbances described in the foregoing pages must have greatly altered the physical geography of the British region. Indeed, it may be said that at the close of these disturbances all the larger physical features of these islands had been roughly blocked out.

The great depressions which had been occupied by the seas of the Carboniferous period were broken up, and new ranges of hills had been raised across them, and thus a new set of physical features were formed. The Scottish hill-ranges were, of course, already in existence, as were also the hilly districts of Wales and the east of Ireland; but the opening of the Permian period found a great range of mountains occupying not only the whole of Southern England, but running westward far out into the Atlantic Ocean, and including all the southern part of Ireland.

Moreover, these western highlands seem to have been connected with those of the eastern region by a hilly tract of less elevation, but still of sufficient height to separate a large depressed area or basin in the south from the plains and lowlands which lay to the north of it. This east and west barrier probably consisted mainly of a series of ridges and valleys which had a general north and south trend, but its southern border was formed by the northern line of Armorican flexures, a continuation of the Glamorgan, Bristol, and Mendip ridges.

Further a low range of undulating uplands connected those of Southern Scotland with high ground over the eastern Midlands of England. Though then of no great height, this was afterwards to be raised into the Pennine Chain.

Lastly, the western border of the English Midlands had been ridged up into the Malvernian range, an uplift in which all the Old Red Sandstone country to the west probably participated, in so far that it was raised into a high-level plateau, far above the plains and depressions in which the Permian and Triassic deposits were accumulated.

Such I conceive to be a general picture of British geography at the time when deposition again became possible, this being due to a general subsidence of Central and Southern Europe, which allowed the sea then occupying the Russian and Mediterranean regions to invade and cover the lower parts of the pre-Permian continent. It also gave rise to the formation of lakes in isolated depressions between the hill-ranges of Western Europe.

In the British region five areas of deposition are found :—

1. A southern area in Somerset and Devon.

2. A midland area in England.

3. A north-eastern area from Durham southwards to near Nottingham, and perhaps farther.

4. A north-western area, including Lancashire, West Yorkshire, Westmoreland, Cumberland, Isle of Man, and Ireland.

5. Certain small areas in Scotland.

As the rocks found in these several areas differ considerably it is necessary to give a brief account of each facies, and it will be convenient to begin with the southern or rather south-western area, because the deposits there found are probably of older date than most of those in the northern parts of the country ; and their formation was preceded by important volcanic disturbances, which have left striking permanent records behind them.

1. The Southern Area.—The Permian deposits of Devon and Somerset, or at any rate their lower portions, cannot be regarded as one continuous and contemporaneous set of strata. They lie upon a very irregular surface of the older rocks, and they vary exceedingly both in thickness and in component materials. They are, in fact, a congeries of more or less local deposits, consisting for the most part of rock-fragments, in the form of angular débris, boulders, gravel, and coarse sand, washed down from neighbouring slopes and valleys into a lacustrine area of deposition. The resulting accumulations have been consolidated into the red breccias, conglomerates, and sandstones which are now exposed for our study.

It is obvious that no general description can be given of such a varied series of deposits; but four distinct types of bouldery and gravelly detritus can be distinguished, and of these brief accounts may be given.

The first of these is the Torbay and Torquay area, where the lowest and oldest deposits are found. Here sandstone and conglomerate sometimes rest on the Devonian rocks, but the beds which seem to occupy the lowest position are dark red and purple clays, used for making bricks and pottery. These "Watcombe clays"[1] appear to have been formed from the disintegration and erosion of the neighbouring red Devonian slates. They are only found over a limited area about $2\frac{1}{2}$ miles from north to south and 5 from west to east, but as they are truncated by the coast they doubtless had a farther eastward extension ; moreover, similar clay recurs on the north side of the Teign valley, so they probably underlie the intervening breccias. They are not more than 100 feet thick, and are probably the first lacustrine deposits that were formed in the great enclosed basin east of Dartmoor.

The clays pass up into stony marls, breccias, and conglomerates, which are characterised by consisting almost entirely of the débris of local Devonian rocks, limestones, grits, and shales, with very few pieces of igneous rock. Of these beds there is about 400 feet ; but north of Watcombe they are succeeded by a series of breccias and sandstones which contain numerous fragments of felspathic lava and some of Dartmoor granite. Many of the blocks of quartz porphyry are from 1 to 2 feet in length, and Mr. B. Hobson has measured some which were 4 to 5 feet long by 3 to 4 feet broad ; and some of the included limestone blocks are nearly as large.

These beds extend to Teignmouth, and thence along the coast to Dawlish, as well as inland under the Haldon Hills and northward to Exeter. At their base west of Exeter are the lava flows already mentioned, and blocks of these as well as of the porphyritic felstones occur in the overlying breccia. It is noticeable, however, that the size of these included fragments decreases from near Dunchidcock both towards Exeter and the north-east and to the south-east toward Dawlish. I quite agree with Mr. Clayden in thinking that both the actual lava flows and the blocks of lava came from the westward of their present locations, and had their sources of origin on the borders of the Dartmoor district.

The thickness of these breccias near Dawlish is probably not more than 600 feet, and they are covered by sandstones with bands of finer conglomerate, which may be from 200 to 250 feet thick. The slope on which they rest must have a considerable pitch, for their base on the eastern side of the Haldon Hills is from 500 to 600 feet above the sea, while eastward within 6 miles their upper surface passes below sea-level.

Crossing the mouth of the Exe another set of sandstones is found, still including some beds of breccia and others of red marl. These beds exhibit the usual lacustrine phenomena of current-bedding, ripple-marks, and sun-cracks. They are much broken by faults, but may be 300 feet thick, and they are succeeded by some 500 feet of red clay and marl, which are now believed to be also of Permian age, since no break has been discovered in the succession. The full thickness of the series near Dawlish and Exmouth may be estimated at 1600 feet; and if the Watcombe Beds come in below, the total thickness may be 2000 feet.

Near Exeter, however, the breccias thin out against a ridge of Culm-measures and are overlapped by the sandstones. They are found again filling a broad depression in the older rocks around Crediton, and running westward across the valley of the Tawe, with an outlier at Hatherleigh and another at Portledge Mouth, on Bideford Bay. A similar tongue of Permian runs westward from Tiverton, and outliers occur to the N.W. of it, as high as 800 feet. From these facts we may infer that Permian deposits covered the whole of Central Devon between the heights of Dartmoor on the south and those of Exmoor on the north.

The deposits in the Crediton valley resemble those south of Exeter in containing many blocks of igneous rock, but they differ in consisting largely of hard grits and black limestones derived from the Culm-measures, with many pebbles of quartz. The materials have clearly come from the rocks bordering the Crediton trough and from the northern slopes of Dartmoor.

It may be doubted whether the Crediton and Exeter breccias extend farther north than the mouth of the Crediton valley. At any rate the whole series becomes much thinner to the northward, and near Silverton and Thorverton the breccias meet and merge into loose gravels, consisting of much smaller stones, which seem to have come from the northward.[1] The stones are chiefly grits, sandstones, and shale-fragments from the local Carboniferous rocks, but there are also grits from the Upper Devonian rocks of Somerset and some limestone pebbles. These beds and the overlying sandstones are not more than 600 feet thick, while the red marls are reduced to 200 feet, and consequently near Burlescombe the whole series is only half as thick as near Exmouth.

Still farther north, where the beds enter the depression or valley between the Brendon and the Quantock Hills, the lowest beds are soft sandstones with some beds of breccia and conglomerate, in which pebbles of Carboniferous limestone and chert are not uncommon, and the total thickness, including the red clays above, is probably less than 500 feet. Similar beds occur near Williton, and still farther west near Porlock on the north side of the Brendon Hills. Hence we must infer that they occupied the southern part of what is now the Bristol Channel, or at any rate a valley which passed through the Channel area outside the north coast of Devon and Somerset.

From the facts above mentioned it is clear that both Exmoor

[1] See E. C. Martin in *Geol. Mag.*, 1908, p. 150.

and Dartmoor must have existed as mountainous districts rising to much greater heights above the lowlands than they do now, and that they were the principal sources of the materials which compose the Permian deposits of Somerset and Devon. The breccias and conglomerates were doubtless fringing deposits, and the basement beds of Somerset may be only contemporaneous with the sandstones which lie between the breccias and the marls near Exeter.

Lastly, we must return to South Devon and follow the traces of Permian rocks in a southerly direction. A small outlier occurs at Slapton on Start Bay, another at Thurlestone west of Kingsbridge, and a third at Cawsand near Plymouth, all very small but yet distinct remnants of the same breccias and conglomerates that occur round Torbay.

Again, fragments of similar red rocks have been dredged at many points off the south-east coast of Cornwall, some of them being rough angular blocks and slabs, and one obtained 7 miles south of Dodman Point is described as "evidently torn from a submarine reef point," and as showing the fresh fracture from the parent rock. There is, therefore, good reason to believe that a submarine outcrop of Permian rocks runs for some distance outside the coast of Cornwall, and its traces have been followed to a point about 12 miles S.E. of the Lizard.

How far Permian deposits extend eastward beneath the Channel and beneath East Devon and Dorset we are at present unable to judge, for no borings east of Sidmouth have yet been carried deep enough to prove their extension in that direction. Neither can we say how far they reached southward, for no deposits of Permian age have been discovered in Brittany.

In Normandy, however, an interesting remnant of Permian beds occurs near Littry, S.W. of Bayeux. They overlie the Stephanian Coal-measures and consist chiefly of red sandstones and limestone conglomerate succeeded by red marls, the whole series being 800 feet thick. They are only found in the basin of Carentan, and not in that of Valognes, and French geologists are of opinion that they are restricted to the former; it is certain that they do not extend far either to the east or to the west, but they may originally have spread some distance to the north. Even if they had no connection with the British Permian, they are interesting as evidence of another lacustrine basin within the same Armorican region.

2. The Midland Area.—Until a few years ago it was supposed that all the red and purple beds which lay between the Trias and the productive Coal-measures of the Midland Counties were of Permian age, and they were divided into Lower, Middle, and Upper groups. As stated on p. 175, the "Lower Permian" is now included in the Coal-measures, and it is doubtful whether the Middle group is really of Permian age.

The most complete succession is found in Shropshire, where the beds which overlie the Keele sandstones are the following:—

3. The Enville marls. 2. The Trappoid breccias.

1. The conglomerate group.

The lowest group consists of red sandstones and marls with bands of conglomerate, and in the Clent Hills there are some layers of cornstone, but no magnesian limestones, and no fossils have been found in them. The pebbles in Shropshire are partly derived from Silurian limestones and partly from Carboniferous limestone and sandstone; in Staffordshire more than half the pebbles are of Carboniferous limestone.

These deposits may very well have been formed in an isolated lake basin fed by numerous streams which flowed off higher ground and were subject to freshets, which enabled them to carry pebbles into the lake. But there is no proof of their Permian age, and as they seem to lie conformably on the Keele sandstones, they may be either the highest local member of the Upper Coal-measures, or they may be of Stephanian age.

There is better ground for regarding the overlying breccias as really Permian, because they are similar to those of Devonshire. They set in at the south end of the Malvern Hills, and occur at intervals along the east side of the Abberley Hills, and thence by Bewdley they range into Shropshire and Staffordshire. They consist of angular blocks of various rocks, especially of rhyolite, hornstone, quartzite, and felspathic tuff which have evidently been derived from Cambrian and Archæan rocks, like those found in the Lickey Hills and near Birmingham, and very probably at other places below the great spread of Triassic rocks which forms the plain of the Midland Counties. They also include many fragments of Llandovery sandstone, and Mr. Wickham King has remarked on the contrast thus presented by the contents of this breccia with those of the conglomerates below. He points out that "the presence of the rocks down to the Woolhope in the Middle Permian limestone-conglomerates, and of the rocks at and below the Woolhope [horizon] in the Upper Permian trappoid breccias, could be explained easily if the area which furnished the material to these Permian limestone-conglomerates had been eroded down as a whole through the Carboniferous limestone to the Woolhope during Middle Permian time, while in the succeeding Trappoid breccia period subaerial denudation cut through the Woolhope limestone and Llandovery sandstones deep down into the Archæan series."[1]

[1] *Quart. Journ. Geol. Soc.* vol. lv. p. 126 (1899).

It must be remembered, however, that breccias are essentially local accumulations, while conglomerates of water-worn pebbles have usually been transported from some distance, and the contrast noted by Mr. King might therefore be explained on the supposition that the two rock-groups represent the detrition of two different districts, the pebbles of the conglomerate beds having come from outside the area in which the breccias were accumulated. Even so, however, the breccias certainly indicate a great change in the physical conditions, and it is probable that there was a considerable interval of time between the accumulation of the two deposits.

From the large size and angularity of some of the boulders in the Midland breccias Professor Ramsay suggested that they had been transported by glaciers or floating ice, and indicated the existence of glacial conditions in the Permian period. Later writers, however, have shown that this is unlikely, and that the scratches which do occur on some of the stones are not necessarily due to ice.

Mr. King's view of their mode of origin is that they are subaerial torrential deposits, formed more or less of talus and scree-débris, swept down in times of flood from the buried tracts of Palæozoic rocks which underlie the Trias to the east and south-east, and which he termed the "Mercian Highlands." In this view Professor Bonney concurs, but points out that the height of these ridges cannot have been great, and that "Uplands" would be a more accurate designation.

Professor Lapworth also remarks that if the Malvern and Charnwood Forest areas are excepted, "no Midland pre-Permian rocks from which these Permian breccias might have been derived attain at present so great an elevation above the sea-level as the Permian breccias themselves, and upon the theory that these breccias are of local origin, it becomes necessary to postulate an upland area, ridge, or series of ridges of high ground crossing the Midlands in Permian times along a N.E. and S.W. line from Charnwood through the southern end of the Lickey Hills, towards the Abberley and Malvern ranges."[1]

Professor Lapworth, however, rather leaves it to be inferred that the strike of the ridges themselves was from N.E. to S.W., whereas in reality he would doubtless agree with me in thinking that the ridges and their intervening valleys ran from N. to S. or from N.W. to S.E., parallel to the strike of the Charnwood rocks and the Nuneaton ridge. It may here be remarked that most of the red sandstones round Coventry, which are coloured Permian on existing geological maps, are probably of Carboniferous age, and that it is doubtful whether any true Permian exists in that area.

[1] *Proc. Geol. Assoc.* vol. xv. p. 375 (1898).

In Leicestershire there are several small patches of breccia and red marl which are usually regarded as Permian, since they rest unconformably on the Carboniferous, and are overlain unconformably by the Trias. Dr. H. T. Brown has paid special attention to them and concluded that 80 per cent of the stones are derived from the Cambrian series, but that some may have come from the Charnwood rocks. Professor Bonney has also examined them and has identified syenite, dacite, and slates from Charnwood, as well as shales, grits, and nodules from Carboniferous rocks.

The breccias occur in bands with intercalated beds of red and grey clay, and it is significant that the breccias thicken southward while the clays thicken northward; hence it becomes a question whether they may not originally have been connected with the northern basin of deposition on the other side of the Trent valley, for the distance between existing outcrops on the N. and S. of this valley is only 13 miles.

It is clear at any rate that the materials of the breccias came from the southward, and that there was high ground in that direction, while if there was a barrier of any kind between the Leicester and Nottingham areas it must have been narrow and of low elevation. It is quite as doubtful whether there was any connection between the Permians of Leicestershire and those of Staffordshire. Perhaps the most probable explanation is that the breccias are really terrestrial deposits washed down during times of heavy rainfall on to the southern margin of a comparatively small lake, which had no connection with any other water-basin or area of deposition.

3. The North-East Area.—The outcrop of the Permian in the N.E. of England is shown in Fig. 30, and the beds are known to extend eastward beneath the newer deposits in East Yorkshire, Notts, and Lincolnshire, and are believed to pass below the bed of the North Sea. They are believed to represent the higher part of the Permian system as developed in Germany, while it is probable that the breccias of the Southern and Midland Counties belong to the lower part; if this is so, it will account for the fact that the N.E. type approaches so near to that of Leicestershire without seeming to have had any connection with it.

The formation is thickest and most purely calcareous in Durham, where it consists almost entirely of magnesian limestone or dolomite, the thickness of which is from 600 to 878 feet (the latter in a boring at Seaton Carew). At the base are a few feet of calcareous shale and soft sand. In South Yorkshire the beds are from 400 to 570 feet thick, but the upper part of the limestone is partly replaced by red marls. In Notts the thickness along the

Fig. 30.—GEOLOGICAL MAP OF THE NORTHERN PART OF ENGLAND.

outcrop is still less, being apparently about 200 feet, of which only 70 or 80 are limestone, and near Kimberley the limestone passes into a yellow calcareous sandstone, underlain by shaly marl with a few feet of hard calcareous breccia at the base. West of Nottingham the outcrop terminates, the Coal-measures rising up from beneath it as if they were sloping up to a shore-line on the south.

Borings at South Carr near Haxey, and at Scarle near Newark, prove that the formation thickens eastward from its outcrop and reaches a thickness of over 500 feet at both places. The first traversed 545 feet of Permian, though at the outcrop near Doncaster they are not more than 400 feet. At Scarle the thickness was still 519 feet, as compared with about 200 at Mansfield, and the increase is quite as much in the limestones, which have a total thickness of 229 feet, as in the marls and sandstones.

These facts show that the Permian beds thin westward toward the Pennine range and still more rapidly southward, whence we may conclude that there was a shore-line in both directions. A boring at Owthorpe, 7 miles S.E. of Nottingham, passed from Trias directly into Coal-measures, but it is not safe to infer from this that Permian beds never existed there. Better proof of the neighbourhood of land is found in the assemblage of stones and boulders that make up the basement breccia; they are principally of sandstone, ironstone, and shale from the neighbouring Coal-measures, but there are also fragments of slate, quartz, and quartzite that may have come from a northerly prolongation of the Charnwood Forest rocks.

With regard to the conditions under which these deposits were formed it is specially noteworthy that borings near Middlesbrough have proved the occurrence of beds of gypsum interbedded with those of magnesian limestone, making it fairly certain that the waters in which their deposition took place were not those of an open sea like the Mediterranean, but of a closed and inland sea like the Caspian. Moreover, though the fossils found in the limestones are marine forms and belong for the most part to Carboniferous genera, the fauna is a small one, and the species also are mostly of small size, as if dwarfed by the conditions in which they lived; points which again suggest a correspondence with the conditions of the Caspian Sea.

Again, the Middle red marls and sandstones of Notts present surfaces which often show ripple-marks, sun-cracks, and annelid tracts, with occasionally the footprints of various kinds of Amphibia or Reptilia;[1] all these plainly indicating variations in the water-

[1] Hickling, *Quart. Journ. Geol. Soc.* vol. lxii. p. 125; and *Mem. Manch. Phil. Soc.* vol. liii. (1909).

level of the great lake and times of greater evaporation, when the waters receded so as to expose large tracts of desiccated mud and sand.

The sequence of events in the north-eastern area was probably as follows. The first deposits were sands, shales, and calcareous sandstones, formed chiefly along the borders of the basin, but after a time the inflowing streams carried less sediment in suspension and more material in solution, especially salts of lime and magnesia, so that chemical precipitation began to take place. In the northern part of the area such chemical formation of magnesian limestone was almost continuous, but in the southern it alternated with episodes of ordinary sedimentation; these alternations of chemical and mechanical deposition doubtless depending on periodic variations in the relative amounts of sunshine and rainfall, dry seasons causing great evaporation and much chemical precipitation, while wet years would swell the streams and cause the formation of marls and sandstones.

4. The North-Western Area.—Rocks of Permian age are found again in Lancashire, Westmoreland, and Cumberland, but the deposits in this area are different both from those in the Midlands and from those on the eastern side of the Pennine range.

They are everywhere divisible into two stages—a lower consisting of bright red or variegated sandstones, varying in thickness from 300 to 1500 feet, and an upper group of red clay and shales, with one or more bands of magnesian limestone, which latter sometimes contain shells of the same dwarfed marine types as occur in the Durham and Yorkshire limestones.

In South Lancashire these beds border the coalfield from a point north of Macclesfield, by Stockport and Manchester, to a point south of Wigan, where they are overlapped by the Trias. They were formerly supposed to extend under the Trias towards Liverpool and under the great Cheshire plain, but Dr. A. Strahan pointed out in 1881[1] that the beds taken to be Permian near St. Helens were really of Triassic age, and that there was no evidence for the existence of Permian below the Trias west of Warrington. Between Stockport and Warrington, therefore, the width of the area from east to west occupied by Permian seems to be less than 20 miles (see map, Fig. 30).

Northward it must have covered a wider area, for small outliers of Permian sandstone occur near Euxton, and east of Preston others overlie Carboniferous limestone near Clitheroe, and a larger patch overlies part of the Ireton coalfield on the Yorkshire border. Permian Beds are also found on both sides of the Lake District, and are well developed in the Eden valley, where the lower beds

[1] See *Geol. Mag.* for 1881, p. 433.

are known as the Penrith Sandstone and the upper as the Hilton Beds.

At the south end of the Eden valley by Kirkby Stephen and Appleby (see map), the Penrith Sandstone includes two thick bands of breccia, locally known as "brockram." One lies at the base and consists entirely of angular fragments of Carboniferous limestone, dolomitised and embedded in red sandstone ; the other near the top is similar, but contains pebbles of quartz and blocks of conglomerate derived from the basement bed of the Carboniferous series on the eastern side of the valley. Hence it is clear that this basal conglomerate was exposed when the upper "brockram" was formed, and it may be inferred that the Pennine fault was either mainly pre-Permian or produced in the interval between the formation of the two beds of breccia.

Professor Kendall has argued for the latter view, but the facts are equally explicable by the former, for the basal beds of the Carboniferous would not be at once exposed to the action of streams and torrents by a pre-Permian displacement ; much of the overlying mass of limestones and sandstones would have to be cut through before they reached the basal conglomerate. Here it may be remarked incidentally that much of the material of the Permian sandstone was probably derived from the erosion of the Carboniferous sandstones.

The Penrith sandstone is believed to be more than 1000 feet thick, and near Kirkby Stephen both the brockram beds are about 100 feet, but both thin out to the north of Appleby. The sandstones consist almost entirely of quartz, and the grains are frequently as rounded and worn as those of desert sands, making it probable that much of the material was blown along the surface of a dry, arid, wind-swept country before it was carried by streams into the Eden valley or lake. The sandstones are also strongly current-bedded, and the prevailing inclinations of the false-bedding show that the streams flowed from the east off the Pennine area, and not from the Lake District.

Mr. Goodchild was of opinion that all these facts could only be accounted for on the supposition that the beds were formed in a lake which was more or less saline. The absence of mica and felspar grains, he thought, might be a consequence of the undergoing decomposition by the saline water as fast as they were swept into the lake.

The overlying Hilton Beds consist of sandy shales, sandstones, and magnesian limestone ; the shales have yielded plants like those of the German Kupferschiefer ; the limestone only occurs at the top, and varies from 7 to 30 feet in thickness. These beds are not continuous throughout the district, for the Triassic marls lie unconformably upon the Permian, resting sometimes on Hilton Beds and sometimes on the Penrith sandstone. The plant-beds seem to indicate an episode of greater rainfall and a resulting diminished salinity of the lacustrine waters.

On the western side of the Lake District the Penrith Sandstone is only represented by a few patches of sandstone east of Whitehaven and southward to Gosforth, but the thickness is small, and at St. Bees Head there is no sandstone or shale, only a bed of breccia surmounted by 11 to 30 feet of magnesian limestone. It is evident therefore that no deposition took place near Whitehaven till near the close of the Permian period, just before the time when conditions favoured the formation of magnesian limestone.

Red sandstones and brockrams of Permian aspect occur in the Isle of Man near Peel. Their present boundaries are faults, but it is probable that originally they covered all the southern part of the island, while the higher central parts doubtless furnished the materials of the breccias.

In Ireland three small patches occur in Ulster—fossiliferous magnesian limestone existing at Cultra, on Belfast Lough, and at Tullyconnel in Tyrone; and Boulder Beds, with a limestone breccia at the base, rest on the Carboniferous limestone of Armagh. The blocks in the Boulder Beds are chiefly grits and sandstones derived from the Silurian and Old Red Sandstone districts that lie to the north-west.

In comparing the deposits found in this western basin with those of the area to the east of the Pennine range, we cannot fail to be struck by the great contrast in lithological characters; the thick sandstones and small development of magnesian limestone in the west contrasting with the rarity of sand and the great development of limestone in the eastern area. The simplest and most probable explanation of these differences is that the red sandstones of the western area were accumulated in a separate enclosed lake-basin divided from the eastern basin by the ridge of the Pennine anticline.

The Penrith sandstone may thus be partly coeval with the lower part of the magnesian limestone of Durham, and partly of earlier date, and thus homotaxial with the Rothliegende or Lower Permian of Germany, while the Durham limestones are undoubtedly equivalent to the Zechstein or Upper Permian of that country. We may assume, therefore, that it was not till the close of the period that subsidence and extension of the Zechstein waters led to the submergence of the intervening ridge, and allowed the eastern waters to mingle with those of the western lake.

It is a question whether the Permian deposits ever passed completely over the Lake District. It is improbable that the Penrith sandstone did, because it is overlapped by the Trias in passing westward along the northern border of that district, and it is entirely absent near St. Bees Head. I agree, therefore, with Dr. Marr in thinking that the central part of the Lake District cannot have been submerged beneath the Permian lake, but must have formed an island, though probably none of it rose much above water-level at the close of the period. This island may have extended from Cockermouth and Keswick on the north to Broughton and Kendal on the south.

5. **In Scotland** there are several tracts of red sandstone which have been regarded as Permian by some geologists and as Trias by others. Of late years the balance of opinion has been in favour of their Triassic age, but quite recently more distinct evidence for the Permian age of some of the beds has been brought forward.

Thus Mr. D. M. S. Watson has shown that the Reptiles of the Cummingstone Beds in Elgin have their nearest allies in the Permian and not in the Trias; and Mr. G. Hickling has compared the Reptilian footprints of the Annandale sandstones with those of Mansfield, and finds a great similarity between them, two of the types seeming to be identical, while none of the former resemble prints of Triassic age.

The explanation of these doubts and discrepancies is probably that both Permian and Trias are represented in the "New Red Sandstone" of Scotland. Thus in Arran, below beds of red marl and sandstone which are undoubtedly of Triassic age, there are conglomerates underlain by about 1000 feet of bright red sandstone with strong current-bedding, and thus bearing more resemblance to the Penrith sandstone than to that of St. Bees. Again, the lower sandstones of Dumfries, which carry the footprints above mentioned, are overlain by breccias and conglomerates which may be the base of a Triassic series.

In Ayrshire and in the Thornhill basin similar bright red sandstones are interstratified with sheets of contemporaneous lava and volcanic ash; such accompaniments being frequent in the Permian of Germany, but rare in the Trias.

Lastly, in Elgin there seems no doubt that both Permian and Trias are present, and, according to Mr. Watson,[1] the beds exposed along the coast from Cummingstone to Coversea should be classed as Permian. He describes the rock as a moderately coarse yellow false-bedded sandstone, with occasional thin beds of small pebbles; the beds are sometimes flaggy and then exhibit many reptilian

[1] See *Geol. Mag.*, 1909, p. 102.

footprints. East of Elgin a patch of similar sandstone has yielded bones of the reptiles *Gordonia*, *Geikiea*, and *Elginia*, which are allied to species found in the Permian of Russia and of Texas. The pebbles near Elgin are of remarkable shape, being angular wind-cut "dreikanters," and the sand-grains are well rounded, so that the deposits seem to have been formed in a lake which was surrounded by wide and arid wind-swept areas, possibly an oasis in a desert land.

5. *Geography of the British Region*

Having indicated the areas occupied by the Permian deposits and the probable conditions under which they were severally accumulated, we are now in a position to discuss the geography of the region and the limits of the areas of deposition.

With respect to the southern area we saw reason for concluding that the beds were formed in a lake, bordered on the west by a region of high volcanic mountains ; further, that the lake-basin was of considerable size, extending from the eastern parts of Devon and Cornwall over a large portion of the area now occupied by the waters of the English Channel, while its northern part was prolonged into a gulf which stretched westward across the central part of Devonshire to and beyond Bideford. The probable extent of the lake is indicated on the map (Fig. 31), but it must be remembered that its eastern limits are at present entirely hypothetical.

With regard to the manner in which the coarser breccias and gravels were accumulated on the borders of this lake, they exhibit no signs of glacial action, but every indication of very strong currents of water, currents which must in some places have flowed at the rate of 12 to 14 miles an hour. The breccias are, in fact, torrential deposits, and may be regarded as parts of so many *diluvial* fans, such as can be seen in the mountain valleys of Kashmir or Persia, or on the coast of the Riviera, at the present day. The surface on which such fans are spread out may be a mountain valley, or a plain, or a lake-bottom, or the sea-floor ; the essential factors of its formation are : (1) the proximity of steep hill-sides ; (2) occasional heavy rains, by which mountain streams are suddenly swollen into torrential rivers, and enabled to carry down enormous quantities of rock-débris with blocks of a size that could not be moved under ordinary fluviatile conditions.

There is, however, an important point which has not yet been discussed, and this is the question whether the lake waters were salt or fresh ; in other words, whether it was an enclosed lake-basin, or whether a river ran out of it.

There is nothing in the Permian deposits of Devonshire to suggest that the water was salt, except the fact that where they rest on Devonian limestones the latter are generally more or less dolomitised. Such surface dolomitisation is generally attributed to the infiltration of water containing magnesian salts ; but the Watcombe clays do not contain gypsum or rock-salt, nor is either mineral found in the sandstones and red marls which overlie the coarse sandstone and breccia series ; further, it is possible that the dolomitisation of the limestones was accomplished by the downward percolation of water from the later Triassic salt-lake through all the intervening Permian strata.

Mr. Clayden has observed (after reference to the northern salt-lakes) that "we have no evidence of a similar salt-lake in Devon. The sands and marls so closely related to our local breccias do certainly appear to have been deposited in water, and show every sign that the water was shallow and apt to be disturbed by strong currents, such as the torrential rushes we have supposed. But these waters may have been fresh, and the Devonshire lake may have drained northwards into the Midland basin." [1]

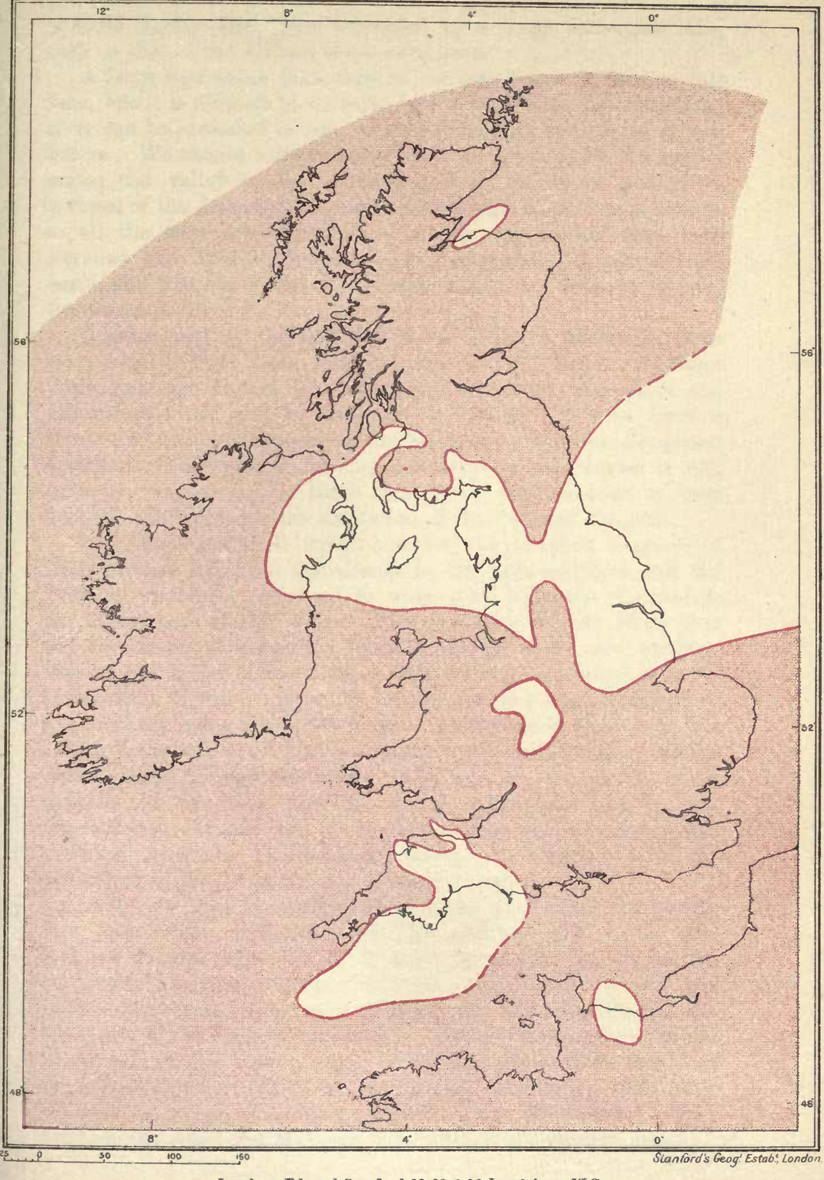
It is quite true that the waters may at first have been fresh, indeed it is very probable that they were, for torrents which could carry down such large angular blocks as are found in the breccias must have furnished a large supply of fresh water, and the annual supply may thus have been considerably greater than the amount abstracted by evaporation from the surface of the lake.

But the diminution in the size of the component fragments and particles as we ascend in the series, and finally the intercalation of marls with the sandstones, seem to indicate a decrease in the rainfall and a cessation of the torrential floods with which the period of deposition had commenced. Consequently, by the time that the red marls were being formed evaporation may have been greater than the inflow, and the water may have become saline, though never sufficiently so for the point of precipitation to have been reached.

I believe this to have been the case, not from any evidence yet obtained from the marls themselves, but from a consideration of the overlying Triassic deposits. So far as the Permian and Bunter Beds are concerned there might have been an outlet from the lake through the northern barrier, for it is most probable that the level of this southern lake was higher than those to the north of the barrier. But if there had been a freshwater lake *with an outlet*

[1] *History of Devonshire Scenery* (1906), p. 97.

Fig. 31.—GEOGRAPHY OF PERMIAN TIME.



London: Edward Stanford, 12, 13, & 14, Long Acre, W.C.

it could hardly have been succeeded by a *larger* salt-water lake, such as that of the Keuper must have been.

A large freshwater lake may be converted into a smaller salt lake, but it is difficult to conceive how a lake with an outflowing river can be increased in size without remaining as fresh as it was before. We should have to assume a local upheaval of the barrier across the valley of the outflowing river so as to produce a reversal of the drainage ; an assumption which is quite unnecessary, as all the facts are explainable on the supposition that both Permian and Triassic deposits were accumulated in an enclosed basin, and that the waters of the lake varied in degree of salinity from time to time.

Coming next to the deposits of the Western Midlands, these seem also to have been formed in an isolated basin. Professor Hull long ago argued for the separation of the Shropshire and Lancashire areas, and he supposed the barrier to have been a transverse anticline connecting the Bala fault with the Congleton anticline. The evidence for such a location of the barrier is not, however, very strong, for these Lancastrian flexures seem to have had little influence on the limitation of the Permian deposits.

Since Professor Hull wrote, however, the so-called Permian of Denbighshire has been transferred to the Coal-measures, and the Permian system is restricted to what were formerly regarded as the higher beds of that series. This has made it more likely that the two areas of deposition were separated from one another, because the space between the actual Permian outcrops is much wider than it was supposed to be, the distance from Shrewsbury to Stockport being about 50 miles. At the same time it is not easy to locate the exact position of any pre-Permian ridge ; further investigation is required before it is safe to do so, for much depends on the true position of the Alberbury breccia near Shrewsbury. It has yet to be determined whether that passes eastward into the Conglomerate group, or whether it is the equivalent of the Trappoid and Haffield breccias.

Lastly, we have to consider whether the north-west and north-east areas were connected with one another, and I am still inclined to the view which I took in 1892, that there was eventually a water-connection between them, though it may not have been a broad one, and it probably did not exist during the formation of the Penrith sandstones. The occurrence of magnesian limestones in the western area, containing semi-marine fossils of the same kinds as those in the eastern limestones, tells very strongly in favour of water-connection across the Pennine ridge ; for how else could the Mollusca have reached the western area ?

This conclusion is not inconsistent with the acceptance of a pre-Permian date for the Pennine uplift, for the ridge then produced has been greatly modified by subsequent uplifts, and at the present time the range is divided into two more elevated areas, where the highest ridges now exceed 2000 feet, by an intermediate tract in Yorkshire, where they do not exceed 1700 feet. If this was a Permian feature it may have been across this tract that the waters of the eastern basin made their way into the western district, and led to the formation of the upper stage of shales and magnesian limestones both in Cumberland and Lancashire.

The western lake basin must have been of considerable size, for there is good reason to believe that its waters covered nearly the whole of Lancashire, with large parts of Westmoreland and Cumberland, and that it sent arms northward up the valleys of the Nith and Annan. As to its westward extension we may infer, from the presence of Permian sandstones both in Ireland and in the Isle of Man, that it occupied the greater part of what is now the Irish Sea, and that it covered the N.W. corner of Ireland as far as the borders of Cavan, Monaghan, and Tyrone. Thence a gulf probably extended into the Firth of Clyde and Ayrshire, and this may have been connected with the Nithsdale inlet, converting the uplands of Wigton and Kirkcudbright into an island.

We have already seen reason to conclude that the central part of the Lake District was also above water, and consequently an island in this Permian lake.

With regard to the southern border of the lake, we have seen that it is not likely to have extended southward into the Midlands, but that it narrowed into a bay or gulf in South Lancashire. Its waters do not seem to have touched any part of Wales, and we must suppose that its southern shore passed westward along a line between North Wales and the Isle of Man.

The beds formerly regarded as Permian in Anglesey are now referred to the Trias, and there is no reason to suppose that the Permian lake infringed upon the broad tract of highlands which bridged St. George's Channel. In all probability the pre-Permian uplifts had greatly increased the relative height of St. George's Land above the sea-level, so that its mountain ranges were then far more imposing than the dissected remnants which have survived the long-continued detrition of the subsequent Mesozoic and Tertiary periods.

In Fig. 31 I have endeavoured to show how the northern basins may have been restricted in the early part of the period, and how a much wider space was occupied by the later inland sea.

CHAPTER IX

THE TRIASSIC PERIOD

THE areas occupied by the Trias in England can be seen on any geological map, and the position of these areas makes it clear that the principal hilly and mountainous regions of the country were already in existence before the deposition of the Trias. The chief exceptions are the Lake District of Westmoreland and Cumberland, which is now believed to have been part of the Triassic lowland, and to have acquired its greater relative elevation at a much later date ; and secondly the Mourne Mountains of Ireland, which are also of similar late elevation.

There were, however, other tracts of somewhat high and hilly ground in early Triassic time which are not made apparent by mere inspection of a geological map of England. On such a map the outcrop of the Trias appears to be almost continuous from Durham in the north-east to Devon in the south-west, but it must be remembered that this is mainly the outcrop of the Upper and not of the Lower Trias, which is much more restricted in its extension. The boundaries of the Lower or Bunter division are in many places concealed by the nearly horizontal spread of the upper beds, but the south-eastern limit of the northern Bunter can be approximately traced by means of the deep borings which have been made at many places in the Midland and Eastern Counties ; so that it is possible to construct a sketch map of the restricted area occupied by the Bunter in the Midlands, and thus to show how widely it is separated from the contemporaneous deposits in the South.

Such a map is essential to the comprehension of the conditions under which the Lower Trias was accumulated, and is supplied in Fig. 32, from which it can be seen that the space between the two areas is substantially the same east and west barrier which had existed in Permian time. The height of its ridges had doubtless been reduced by subaerial agencies, but it still remained as a tract

Fig. 32.—MAP SHOWING THE PROBABLE ORIGINAL LIMITS OF THE BUNTER AND KEUPER DEPOSITS.

of hilly ground connecting the highlands of Wales with another area of highland which now lies buried under our Eastern Counties. This point will be brought out more fully in the following pages.

The nomenclature of the British Triassic deposits has been taken from that of Germany, because there is a general resemblance between them, though our series is less complete. In Germany the system is so plainly and naturally divisible into three sets of beds that the very name of *Trias* is derived from the fact. These divisions are :—

3. The Keuper (red marls and sandstones).
2. The Muschelkalk (mainly marine limestones).
1. The Bunter (variegated sandstones and shales).

In the British region nothing comparable with the Muschelkalk is found, so that only the Lower and Upper divisions of the Trias are represented in this country. Of the distribution and component materials of these two divisions some account will now be given, dealing first with the Bunter and then with the Keuper.

1. Lower Triassic Time

A. *Stratigraphical Evidence*

In most parts of England there is a certain amount of unconformity between the Permian and the Bunter, but it is not so great as some have supposed, and it does not indicate any great terrestrial disturbance. In the northern and central parts of the country there seems to have been some tilting of the Permian Beds and some rupturing of the older rocks by faults during the interval, and this interval may have been a considerable period of time ; but the physical changes were not great, for the Bunter deposits practically occupy the same areas as the Permian, though in many places it is evident that they passed over and beyond them, so as to cover wider spaces.

1. **Southern Area.**—In this area there is so little break between Permian and Trias that it is uncertain where the line of separation should be drawn ; but the balance of opinion is in favour of including the Lower Red Marls in the Permian, and consequently of regarding the overlying "Pebble Beds" as the base of the Triassic system. These Pebble Beds are well exposed on the coast at Budleigh Salterton, where they are about 70 feet thick, and pass up into coarse, current-bedded red sandstones. From the coast they can be traced inland to Williton in Somerset.

The Budleigh pebbles have attracted attention for a long time because some of them contain fossils. These fossils were studied by Messrs. Salter and Vicary in 1864, and by Mr. Davidson in 1869 ; about sixty species have been obtained, some of them being Devonian and some Ordovician. Among the latter are many species which do not occur in England, or at any rate in any rocks which are now exposed in this country, but are of common occurrence in the Ordovician rocks of the N.W. of France.

More recently the pebbles themselves have been studied by Professor Bonney [1] and Mr. O. A. Shrubsole.[2] The former describes the majority of the pebbles as being from 3 to 5 inches long, but some of them as 8 and 9 and even 12 inches long. The prevalent rock is quartzite, but of several varieties and colours, some compact grey, reddish or purplish, some speckled and felspathic ; there are also felspathic grits, dark-green tourmaline grits, quartz-pebbles, some felstones, and occasional pieces of rotten granite.

Comparing the quartzite pebbles with those of the Midland Bunter Beds, Professor Bonney states that at Budleigh the speckled quartzites are the commonest, while in the Midlands the more compact, reddish, and liver-coloured quartzites are the dominant kind. He notes also the remarkable fact that specimens of a peculiar hard, red, quartz-felspar grit occur in both districts, this rock being indistinguishable from the Torridon sandstone of Scotland ; but, as he admits in a later paper, it also closely resembles some parts of the Grès felspathique of France.

Of the assemblage as a whole he remarks that it could not well have been derived from rocks now exposed in Devon and Cornwall, though some of the stones could be matched there. He does not suppose it to have come from the same source as the pebbles of the Midlands, but agrees with the view that it must have been derived from sources to the south and south-west of Devon.

Mr. Shrubsole lays especial stress on the fossil evidence, and thinks that it is sufficient of itself to decide the question. The Budleigh pebbles have yielded twenty-five species of Ordovician fossils, and all of them occur in the Grès de May or Grès Armoricain of Normandy. Of Devonian species thirty-six have been obtained, and though many of them occur in Devon and Cornwall, all of them are also found in Brittany. Hence Normandy and Brittany, or land connecting both with Cornwall, could have furnished all the fossils and all the pebbles found at Budleigh. "If they were brought by a single large river, that river doubtless drained a considerable area, including probably the Calvados district of Normandy, part of the Channel area, and possibly part of Brittany, and the

[1] *Geol. Mag.*, 1895, p. 75.
[2] *Quart. Journ. Geol. Soc.* vol. lix. p. 311 (1903).

general direction of its flow must have been northward" (*op. cit.* p. 322).

If any doubt of such a conclusion remained it would be dispelled by the results of the examination of the sandy matrix of the pebble bed made by Mr. H. Thomas.[1] He found that the percentage of grains of heavy minerals in the sand decreases northward from Budleigh to Burlescombe, but at that place it rises again, several other minerals at the same time making their appearance. Hence he infers that the main current from the south was joined near Burlescombe by another current from a westerly direction. Again, he found that grains of staurolite are very common in the southern part of the outcrop, a mineral which is not known to occur in Devon or Cornwall, but which is fairly abundant in the schists and gneisses of the N.W. of France. He therefore came to the same conclusion as those who had investigated other lines of inquiry.

Finally, there is the fact that the quartzite pebbles which are so large and abundant near Budleigh are gradually replaced toward the north by smaller pebbles, mainly of grit and quartz, till at Tallaton and Burlescombe the bed becomes a sandy gravel composed of small quartz and grit pebbles.

We may next consider the probable southerly continuation of the Pebble Bed. No doubt it actually extends for a considerable distance below the floor of the Channel at the present time; we may certainly suppose that it is continued southward parallel to the east coast of Devon, and a prolongation of the inland line of outcrop would carry the submarine outcrop to about 40 miles west of Guernsey.

As a matter of fact it appears to lie some distance farther west, for recent explorations by Mr. Crawshay, of the Plymouth Marine Biological Station, have disclosed the interesting fact that pebbles of quartzite, very like those of Budleigh, are common on the Channel floor in depths of 40 to 50 fathoms to the S.E. of Cornwall.[2] They were dredged at many points from 15 to 50 miles S.S.E. of the Eddystone, the farthest being about half-way between the Lizard Point and the Isle de Batz on the coast of Brittany, and about 90 miles west of Guernsey. Mr. R. H. Worth describes the stones as of various colours, purple, red, light red, buff, grey, and white; purple stones being the most abundant.[3]

Moreover, the quartzites are associated with pebbles of very hard quartz-grit, with others of red sandstone, red marl, marly limestone

[1] *Quart. Journ. Geol. Soc.* vol. lviii. p. 620 (1902).
[2] *Journ. Mar. Biol. Assoc.* vol. viii. p. 99 (1908).
[3] *Ibid.* p. 142.

and Liassic limestones; while, as mentioned on p. 199, slabs of Permian conglomerate have been obtained from a submarine reef inshore of these localities. Consequently there is every reason to believe that most of the stones on the floor of the Channel are not far removed from the outcrops of the rock-beds to which they belong.

No Triassic deposits are known to occur in Brittany nor in the Channel Islands, but they are found in Normandy, and it may be worth while seeing whether they throw any light on the question. They consist of pebble beds, sandstones, and marls, but their total thickness does not exceed 200 feet, and as they are succeeded conformably by Rhætic and Lias, they are almost certainly of Keuper age. Their position and limitation, however, are of especial interest, for M. Bigot has pointed out [1] that they lie in an elongate depression or valley excavated out of the Palæozoic rocks, narrowing towards a point near Falaise, and widening towards Bayeux and the basin of Carentan, *i.e.* in a north-westerly direction. Here therefore we seem to have one of the valleys through which pebbles were conveyed northward in Triassic times, and we may reasonably suppose that in Bunter times it was occupied, permanently or occasionally, by a river which conveyed pebbles into the Channel area. The typical outcrop of the Grès de May is actually on its eastern border, and pebbles from that quartzite source would undoubtedly have travelled by this valley-way to the northward.

So far our attention has practically been concentrated on the pebbles of Budleigh Salterton and their distribution both southward and northward, but when we pass out of Devon into Somerset we meet with a different assemblage of pebbles, which seems to have come from quite a different direction. This assemblage has recently been discussed by Mr. E. C. Martin, from whose paper [2] the following account is compiled, and to whom I am indebted for permission to reproduce the map with which his remarks were illustrated (see Fig. 33).

The change in the character of the Pebble Bed takes place near Burlescombe, and is complete at Thorne St. Margaret, where the bed has lost its loose gravelly character and has become a calcareous conglomerate, consisting of pebbles of limestone, quartz, and grit in a matrix of calcareous sandstone. The limestone of the pebbles is grey not black, and some of them are silicified; not a few of them are fossiliferous, containing Corals and Brachiopods, which suggest derivation from Welsh or Mendip limestones rather than from the dark limestone of Bampton, in which fossils other than crinoid

[1] *Bull. Soc. Géol. de France*, p. 949 (1904).
[2] In *Geol. Mag.*, p. 160 (1909).

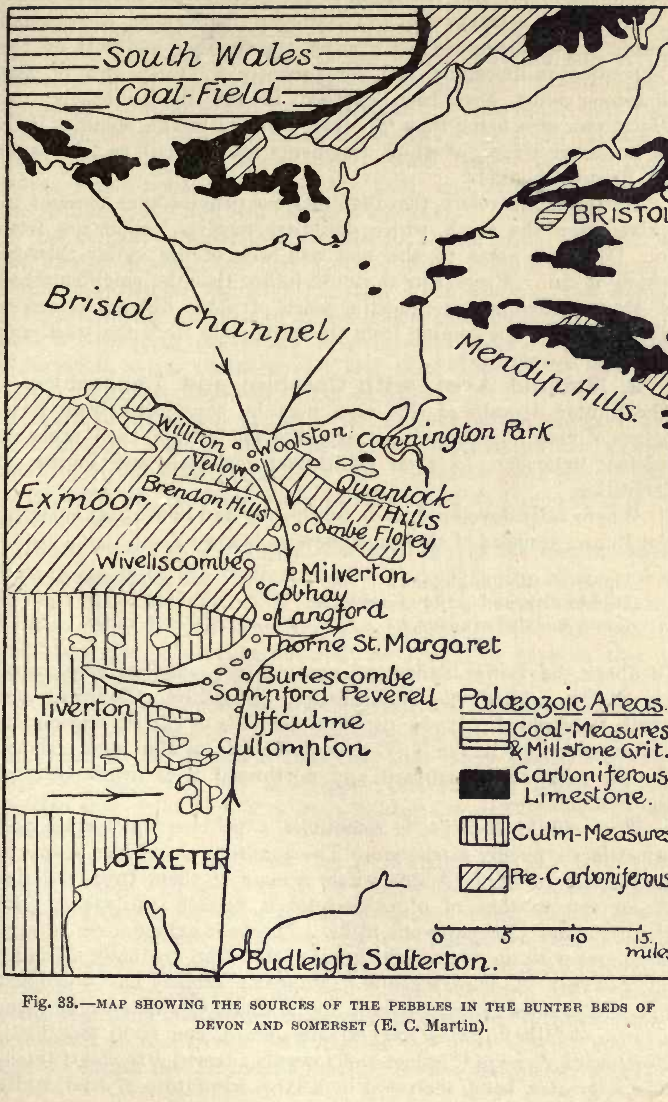


Fig. 33.—MAP SHOWING THE SOURCES OF THE PEBBLES IN THE BUNTER BEDS OF DEVON AND SOMERSET (E. C. Martin).

fragments are rare. Moreover, these fossiliferous pebbles are equally common at Vellow and Woolston, to the north of the Brendon Hills.

Mr. Martin remarks that in Glamorgan, the Keuper, Rhætic, and Liassic deposits successively overlap one another and rest on the Carboniferous limestone, and consequently a larger area of this limestone must have been exposed in the Bunter epoch; the Glamorgan area being then "probably united to the Mendip Hills by limestone ridges, of which fragments still remain as islands in the Bristol Channel."

He thinks, therefore, that the limestone pebbles were brought by a river from the north, which doubtless received tributaries from the Devonian areas to the east and west of the valley through which it ran. From this it would follow that the neighbourhood of Burlescombe was the meeting-place of three distinct rivers or river currents, one coming from the north, one from the west, and one from the south.

2. Midland Area, with Cheshire and Lancashire.—The Bunter deposits of this area may be considered from three points of view: (*a*) the present extent of the beds, (*b*) their probable original extension, (*c*) their component materials and sources of derivation.

Where fully developed, as in Shropshire and South Staffordshire, the Bunter consists of three members as below:—

Upper mottled sandstone	300 to 500 feet
Pebble Beds and pebbly sandstones . . .	300 to 400 ,,
Lower mottled sandstone	300 to 600 ,,

Of these the Lower Sandstone occupies the smallest area, being practically limited to Staffordshire, Shropshire, Cheshire, and South Lancashire. It also occupies the Vale of Clwyd, and doubtless extended far to the N.W. toward the Isle of Man and Ireland. To the southward, eastward, and northward it is overlapped by the Pebble Beds.

The middle division is sometimes a pebble-conglomerate and sometimes a pebbly sandstone. The quantity of pebbles seems to be greatest in Staffordshire, where a mass of them from the size of an egg to that of a man's head is banked up against the Permian and Carboniferous rocks. The beds extend over a very large area with an average thickness of 300 feet, gradually thinning out eastward in Warwickshire. Professor Bonney has calculated that the pebbles of these beds in the Midland Counties would form a range of hills 20 miles long, 2 miles broad, and 1000 feet high. Northward through Cheshire and towards Liverpool the total thickness is greater, being increased by a large admixture of sand, while the quantity and size of the pebbles appear to diminish, so that the deposit passes into a pebbly sandstone from 600 to 750 feet thick.

The Upper Sandstones have a wider extension than either of the lower divisions, for commencing at the southern end of the Malvern Hills, they extend northward through Worcestershire, Shropshire, Cheshire, and Lancashire, and overlie the Pebble Beds round Birmingham and in South Derbyshire. In North Lancashire the Upper Sandstones cannot be separated from underlying sandstones, which contain some pebbly beds, and probably represent the middle group, the two having a thickness of 1300 feet.

Let us next consider the evidence for the original extension of the Bunter deposits, and first that for their eastern subterranean limit, as shown on the map (Fig. 32). The whole of the Bunter is known to die out east of Birmingham and Sutton coalfield ; it does not reappear round the Warwickshire coalfield except near Polesworth, at its northern end, and as a thin pebble bed in a boring at Market Bosworth in Leicestershire.

Southward the beds extend to Bromsgrove on the one hand and to Stourport on the other, being then overlapped by Keuper sandstones, but underground they are doubtless continued at least as far south as Worcester, and probably as far as Upton or even to Tewkesbury.

With respect to the original western limit of the Bunter, some interesting facts are forthcoming. It is of course obvious that it must have extended to a certain distance beyond its present borders on to the Palæozoic rocks of Hereford, South Shropshire, and Denbigh. There is, however, no reason to suppose that it extended very far in a westerly direction.

On the eastern side of the Malvern and Abberley Hills the Lower Sandstones and Pebble Beds are concealed under the overlap of the Keuper, but it is clear that they never passed westward over the hills, for only the Upper Sandstone is found on the western side of the boundary fault, resting directly on the Permian breccia.

It was formerly supposed (by W. Phillips and E. Hull) that this hill range had acquired all its present features before Triassic time, and that it formed a shore-line against which the Trias was deposited. Professor T. Groom, however, has shown that there is no ground for this view. He points out that the eastern boundary fault is of post-Liassic date, and he believes that the existing range of hills is merely the western border of the original range, its eastern portion having been faulted down so that it now lies buried beneath the Triassic deposits of Worcestershire (see p. 174).

How broad this Malvernian ridge may originally have been we do not know, but it must be regarded as merely an exposed portion of the Palæozoic rock-surface which during Permian time stretched across England from west to east, and was probably only one of several similar ridges. If, therefore, we could strip off the newer deposits, we should probably find that the Bunter sands and Pebble Beds ended in a valley or depression between two of these ridges.

In Shropshire the Bunter must have covered the Permian and Carboniferous rocks of the Coalbrookdale and Shrewsbury districts, and from its greater thickness in this county it might be thought that it may have covered some of the ground to the S.W. of these districts ; but many parts of this ground rise to more than 1000 feet above the sea, and allowing for the great amount of denudation which it has suffered since the Triassic period, it is certain that during that period it must have formed a high-level plateau far above the level of the Triassic plain.

The same may be said of the Palæozoic areas of Denbigh and Flint. The Pebble Beds may have covered the Denbigh coalfield, but they are not likely to have passed over the ridge of Moel Fammau, which separates it from the Vale of Clwyd. They and the overlying sandstones may have spread round the northern end of this ridge and up the vale, as well as over the low ground bordering the north coast of Denbigh. They may also have covered a considerable part of Anglesey, for little of that island rises to more that 300 feet above the sea, and there are red sandstones above the Coal-measures, which are now believed to be of Triassic age.

Passing to the Pennine area we may assume that the North Staffordshire and Cheadle coalfields were completely overspread by the Pebble Beds, which now border them, and of which a large outlier extends on to the Pendleside Beds around Leek. Eastward, however, toward Derby, the beds become thinner and are reduced to fringing conglomerates, which are not likely to have extended far northward over the Carboniferous rocks.

Lastly, we have to consider the component materials of these Bunter deposits, and the sources from which they may have been derived.

The Lower Sandstones are chiefly remarkable for the well-rounded shape of the quartz-grains of which they consist, and for the frequent occurrence of the "Millet-seed Beds," first described by Dr. Sorby and Mr. J. A. Phillips. There are friable sandstones, the grains of which are so completely rounded and smoothed that the disintegrated sand flows through the fingers as easily as seed or shot. Such sandstones are frequent in the Lower Bunter, and occur also in the upper division. Ordinary sandstones consist of more or less angular grains (see p. 8), and Mr. Phillips, after having examined a number of modern sands, states that "none of them, excepting such as had long been subjected to the wearing effects of wind action, were found to resemble those of the Millet-seed sandstones in having all their grains reduced to a pebble-like form. Among these the grains of blown desert-sands most completely resemble those of millet-seed sandstone." From these facts we may infer that such sandstones are of æolian formation, and that during the epoch of the Bunter Beds large desert tracts, with their usual accompaniment of blowing sands, existed in the British region.

The Pebble Beds have been the subject of special study by Professor Bonney, who has described the different kinds of pebbles, and has discussed their sources of origin in a series of papers published from time to time between the year 1880 and 1900. From his accounts it appears that the majority of the pebbles in Staffordshire and Shropshire are quartzites, but that various other rocks occur, the commoner kinds and their average proportional numbers being roughly as follows :—

	Per cent.
1. Quartzites of various colours	60 to 70
2. Vein-quartz pebbles	10 to 20
3. Hard grits (coarse and fine)	10 to 15
4. Igneous rocks (felstones, etc.)	4 to 6
5. Carboniferous rocks, sandstone, limestone, and chert	3 to 6
6. Tourmaline grits	1 to 2

The commonest pebble is that of a hard, compact fine-grained quartzite, white, grey, or liver-coloured (purplish); of these quartzites Professor Bonney remarks that they "differ from those of Hartshill, the Lickey, and the Wrekin district. They have also an extraordinary likeness to quartzite pebbles in Old Red Sandstone and Lower Carboniferous conglomerates of Southern Scotland, and to the quartzites of the Northern and Western Highlands, a liver-coloured variety of which, as I have been informed, occurs in the island of Jura."

There are, however, other quartzites, of less common occurrence, which contain *Orthis budleighensis*, *Lingula Hawkei*, and *L. Leseueri*—Ordovician species which have not been found in any British locality except in the Budleigh pebbles, which, as we have seen, were derived from land between France and Cornwall.[1]

Among the pebbles of hard sandstone and grit there is one kind which consists mainly of quartz and felspar, and of which,

[1] Mr. Etheridge identified the *Orthis* found at Gorran Haven in Cornwall as *O. budleighensis*, but it is now referred to *O. calligramma*.

writing in 1886, Professor Bonney remarked: "The rock macroscopically and microscopically presents an extraordinary resemblance to the Torridon sandstone of N.W. Scotland, and differs from every other rock which I have seen *in situ* in any other part of Britain." It must be remembered, however, that such a quartz-felspar grit is not confined to Scotland, but is found in the Sparagmite of Norway and in the Grès felspathique of Northern France.

Other hard grits and sandstones, resembling the Llandovery sandstone of the Lickey, are by no means uncommon, and some of them contain characteristic Llandovery fossils, so that there can be no doubt of their being of more or less local origin. The tourmaline-grits have not yet been identified with any actual rock *in situ*, but similar pebbles occur at Budleigh. Mr. Fearnsides, however, has recently stated that the tourmaline-grits of the Midland Bunter "bear a striking resemblance to the basal Ordovician grit of Llanberis." [1]

With regard to the felstones Professor Bonney found them to include quartz-porphyries, rhyolites, and mica-felsites. He compared them with many specimens from different sources, but was unable to identify them with any from Shropshire, North Wales, or the Lake District or Devon; on the other hand, he found them to correspond very closely with rocks from the West Highlands and Southern Uplands of Scotland.

The pebbles of Carboniferous rocks are most abundant in Staffordshire (Cannock Chase), and have doubtless been derived from the neighbouring Pennine ridge.

From the above statements it will be seen that many of the pebbles, and especially the predominant quartzites, seem to have come from the western side of Scotland; that some of the stones have certainly been derived from local sources, especially from such Silurian outcrops as must be of wide occurrence beneath the Southern Midlands, and some from the Pennine Carboniferous rocks. Lastly, there are fossiliferous quartzites which can only be matched in the far South, and there are some other pebbles, *i.e.* quartz-felspar and tourmaline grits, which could equally well have come from southern sources.

This is a curious assemblage of rock-fragments, and it is not easy to see how they can have been collected and deposited all round the southern end of the Pennine range, as well as all round the South Staffordshire coalfield; for though the relative proportions of the different pebbles vary in different localities, the same kinds of rock appear to occur throughout the Midland area. Moreover, quartzites always preponderate, and the Bunter con-

[1] "Geology in the Field," chap. xxxii. p. 819, *Proc. Geol. Assoc.* (1910).

glomerates thus exhibit a strong contrast to the Permian breccias and conglomerates.

The probable method in which the Pebble Beds were accumulated will be discussed later on, but we may here notice a fact of some significance. It has been stated that parts of the Lower Bunter Sandstone resemble desert sands in the character of their component grains; it is, therefore, important to know whether the sand of the Pebble Beds is of a similar character. Professor Bonney has examined the sand which forms the matrix of the beds on Cannock Chase, and finds "that while rounded grains occasionally occur, the majority are more or less angular; hence material presumably water-borne dominates considerably over wind-borne."[1]

3. North-Eastern Area.—The Bunter of the Midland area is connected with that on the eastern side of the Pennine range, but the connecting tract is a narrow one (see map, Fig. 31). In Nottingham and South Yorkshire it consists of a lower orange-coloured sandstone overlain by pebbly sandstone of the usual character. Near Nottingham the total thickness is only about 200 feet, but it increases northward, and was found to be 620 feet thick in a boring at Barlow near Selby. It is also thick to the eastward, as proved by the borings at Newark and Gainsborough. At South Scarle near Newark the beds referred to the Bunter are 541 feet thick, and at Gainsborough the boring traversed 475 feet of red sandstones with pebbles without reaching their base. I have therefore assumed that the border-line of these beds runs from Loughborough to Grantham, and thence north-eastward toward the mouth of the Humber (see map, Fig. 30).

Between Selby and Knaresborough the pebbly sandstone dies out, and north of the latter place beds of red clay and gypsum come in beneath the lowest red sandstone. Finally, near Middlesbrough the beds referable to the Bunter consist of 300 to 450 feet of red clay with rock-salt and gypsum, overlain by 400 to 500 feet of red and white sandstones. Such beds as these gypsiferous marls could only have been formed in a salt lake, and we must therefore suppose that such a lake existed over the area lying to the north of York.

As regards the pebbly sandstones, it is very likely that they persist beneath the newer deposits S.E. of York and N.E. of Selby, as indicated on the map (Fig. 32). This naturally raises the question of the probable eastern extension of the Bunter as a whole. In considering this matter we must remember that the inland sea of Permian time is believed to have been continuous from England across the North Sea area, Denmark and Holland,

[1] *Geol. Mag.*, 1908, p. 340.

to Germany and Russia. The Bunter deposits practically occupy the same areas as the Permian, consequently they may have had a similar eastward extension, for they are certainly present in the island of Heligoland.

On the other hand, we must remember that between the formation of the Permian and the Bunter deposits there was a considerable uplift of the whole region, and consequently the Bunter may have been formed in disconnected basins, or on desert plains which were only narrowly connected with one another. At the same time it is well to bear in mind that, if the river drainage of the British region had any permanent outlet, it would naturally be eastward into the Germanic region, and not southward into France.

4. North-Western Areas.—It was stated on p. 221 that the Garstang sandstone of Lancashire represents both the Middle and Upper Bunter of the Midlands. Passing beneath Morecambe Bay this recurs in Furness and along the western border of the Lake District, where it is known as the St. Bees Sandstone. It underlies the Carlisle basin, and runs south-east up the Eden valley to Kirkby Stephen. Thus at the present day it surrounds three sides of the Lake District, and there can be little doubt that it also covered all the country on the southern side between Morecambe Bay and the Vale of Eden.

It was the late J. G. Goodchild's opinion that these sandstones spread continuously over the whole of the Lake District, for, as he remarked, the dips observable in the New Red rocks are such as if prolonged would everywhere carry them over the central mountains. Dr. J. E. Marr concurs in this opinion, and writes: "There seems every reason to suppose that, at the close of the Triassic period, the Lower Palæozoic rocks of Lakeland were buried beneath a cover of newer rocks of Carboniferous age and of New Red Sandstone age. . . . Indeed the probability is that the whole of the north of England was covered with Triassic rocks at the end of that time. The similarity between the Triassic rocks on the two sides of the Pennine Chain is sufficient to indicate that they were formed under very similar conditions, and in one physiographical region." [1]

Now one point in the similarity above alluded to is the fact that in the Carlisle basin, below the St. Bees sandstone, there is a set of red clays and shales with beds of gypsum, beds which thus resemble both in character and position the gypsiferous clays of Yorkshire. Like the latter, they can only have been formed in the waters of a saline lake, but as they thin southwards to only 100 feet at Helton in the Eden valley, the two lakes were

[1] Pres. Address, *Quart. Journ. Geol. Soc.* vol. lxii. p. lxxxiv (1906).

probably not continuous at the beginning of the period, and it is doubtful whether they were united till the time of the Keuper marls.

The St. Bees sandstone has all the aspects of a lacustrine deposit, its beds showing ripple-marks, desiccation-cracks, casts of salt crystals, and the foot-prints of Reptilian animals. Moreover, they overlap the Permian to the N.E. of Carlisle, showing that they had a wider extension in that direction, and this increases the probability of their also having had a greater extension eastward from the southern end of the Eden valley. It is uncertain how far these sandstones extended into Southern Scotland, because it is so difficult to distinguish them from the Permian Penrith sandstone.

Triassic rocks are found again at the north end of the Isle of Man, which is nearly half-way between Cumberland and Ireland. Borings there have traversed Keuper marls and salt beds below which are about 800 feet of red and grey sandstones, with basement beds of conglomerate and breccia (80 feet), which may be either of Bunter or Permian age. The sandstones evidently represent those of St. Bees, and the absence of any underlying gypsiferous clays is noteworthy.

From these facts it would seem highly probable that the northern part of the Irish Sea was occupied by Bunter sandstones of the St. Bees type. It is, of course, quite possible that between Ireland and the Isle of Man there may have been a deeper channel occupied by pebbly sandstones of the Liverpool type, but there is no actual evidence of such a channel; for the succession in the N.E. of Ireland is similar to that in the Isle of Man, the Keuper marls being there also underlain by about 800 feet of red and yellow sandstones resting on Carboniferous rocks.

B. *Physical Geography of Bunter Time*

The Triassic period appears to have begun with a general uplift of Western Europe, which caused considerable changes in the physical conditions of the British regions, though there seems to have been little tectonic disturbance and few local upheavals. The chief difference between the conditions of the Permian and Triassic periods must have been climatic, the rainfall becoming so much less that the inland seas and lakes of Permian time shrank at first to small dimensions, and large portions of their floors were converted into desert plains. It was not till the later part of Triassic time that these lowlands were again occupied by permanent waters.

It is further apparent that the geographical changes produced by the uplift must have led to a connection with some other continent where new forms of life had been developed. The Permian forms, which were mostly modifications of Carboniferous species, were completely exterminated, and a new assemblage of plants and animals took their places.

Before we consider the manner in which the British Bunter deposits may have been accumulated, we must form some conception of the general physiography of North-Western Europe at this epoch.

We may commence our survey with the Scoto-Scandinavian region, for there can be no doubt that at this time there was still continuous land between Norway and Scotland, across what is now the northern part of the North Sea. Scotland itself was a mountainous country, and its general elevation above sea-level was probably much greater than it is now. Westward also the land must have been prolonged far into the area of the North Atlantic, the Caledonian ranges being continued south-westward outside the west of Ireland till they met the westerly continuations of the Armorican ranges from Brittany, Cornwall, Devon, and the south of Ireland.

Within this great arc of mountain ranges there was a central region of lesser elevation, toward which the drainage of the mountain regions seems to have been directed, much in the same way as the rivers rising in the mountains which encircle Persia flow into the central plains and deserts of that country.

Within this central area also there were two tracts of fairly high ground : that of St. George's Land on the west, still extending from the south-east of Ireland through Wales to the high plateau of Hereford and Shropshire ; while on the east was another tract occupying the east of England, the southern part of the North Sea, and Belgium. These two areas of hill country met in a tract of lesser elevation across England, which separated a southern basin of deposition from the more northern plains and basins.

The average height of the eastern highland above the plain on which Bunter deposits were laid down may be judged by the thickness of successive deposits formed in Lincolnshire before the highland was submerged. Assuming it to have been submerged by the sea of the Oxford Clay, the thicknesses of the intervening strata may be estimated as follows : Oolitic Limestones, etc., 200 feet ; Lias, 900 feet ; Keuper, 900 feet ; Bunter, 500 feet—making a total of 2500 feet.

Beyond this eastern land lay the great Germanic basin, the level of which must have been lower than any part of the British region, since it was in connection with the outer sea, and the German Trias includes a thick series of marine deposits. Both the German Bunter and the marine "Muschelkalk" are believed to underlie nearly the whole of Hanover and Schleswick Holstein, and they crop out as far west as Heligoland; hence it is very probable that they both extended some distance across the North Sea in the direction of Northern England.

On the other hand, neither Bunter nor Muschelkalk seem to have penetrated far into Belgium or France. They thin out against the eastern side of the Ardennes region; the outliers of Malmedy and Stavelot being, in the opinion of Professor Gosselet, deposits formed in mountain valley-lakes, and consequently they may be of any age, from earliest Bunter to latest Keuper. The main mass of the German Bunter and Muschelkalk thins out on the south side of the Ardennes, near Arlon, and is overlapped westward by the Lias. Southward it occupies the Vosges country, and doubtless underlies the Departments of the Meuse, Haute Marne, and Côte d'Or, but is overlapped to the south-west by the Keuper, which is the only member of the Trias to emerge on the flank of the Central Plateau of France.

From the above statements it will be seen that there is no ground for supposing that either Bunter or Muschelkalk passed under the Paris basin. It is probable that the Armorican ranges were at this time more or less continuous through the north of France from Normandy to the Ardennes, though they had doubtless suffered greatly from atmospheric detrition, and transverse valleys were probably being cut across them by the streams to which they themselves gave rise. There is a small area of Trias in Normandy, but it is of Keuper age, and neither it nor the Lias extends so far eastward as Havre, where a boring found Silurian rocks below the Bathonian or Great Oolite.

From this brief geographical survey an important general inference may be drawn, which is, that if the internal drainage of the British region had any outlet, it must have been eastward across the North Sea, and not southward or south-eastward through France.

Let us now consider the areas in which deposits were being accumulated, and begin with the southern basin, which presents fewer difficulties than is the case with the northern areas.

We have seen that in Devonshire the Trias succeeds the Permian with apparent conformity, but with a great and sudden change from fine argillaceous sediment to a mass of large pebbles. The superposition of a pebble bed upon a clay without any signs of erosion at its base is an unusual circumstance, and one which is not easy to explain.

We might suppose that the Permian lake-bed had been completely dried up and the mud so hardened by exposure to sun and wind as to offer much resistance to erosion, but in that case its surface would have been traversed by sun-cracks which would have been filled by sand or by portions of the overlying Pebble Bed. No such cracks are to be seen at Budleigh; on the contrary, Professor Bonney has specially noted that there is a kind of passage between the matrices of the two beds, the lowest few inches of the Pebble Bed having a more marley or clayey matrix, *i.e.* a mixture of sand and clay. It is quite possible, however, that the Permian lake had become so silted up by the quiet deposition of the red clays that it finally presented a broad expanse of shallow water covering a floor of stiff and sticky clay.

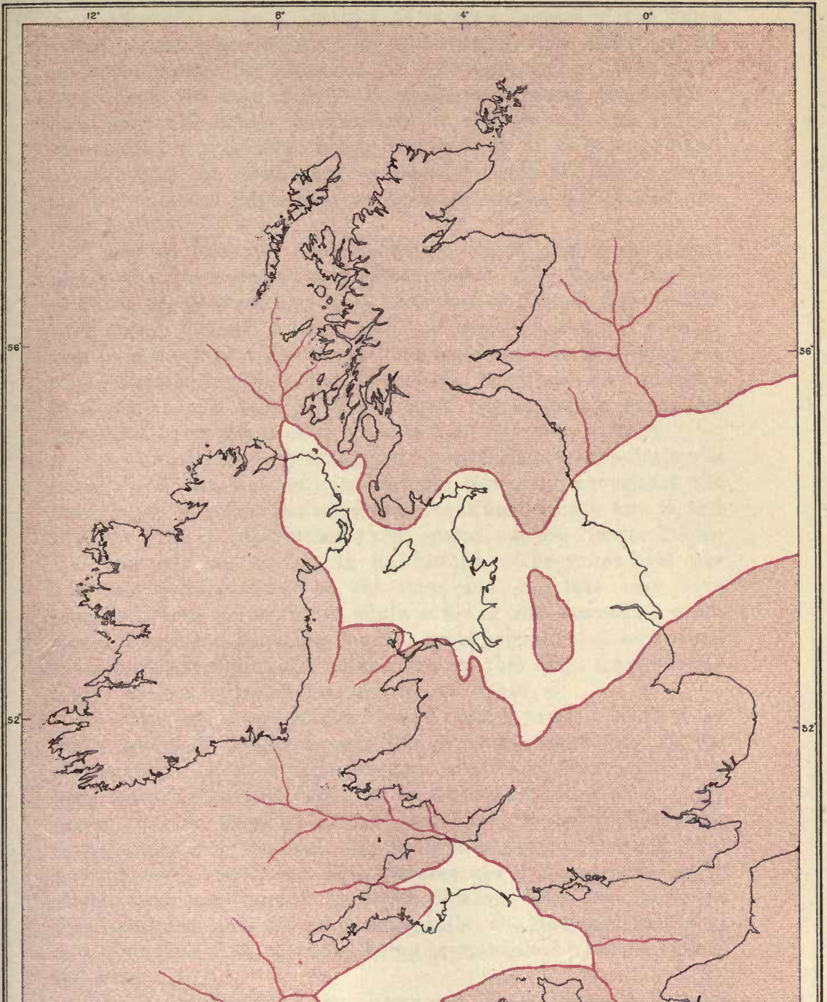
Again, it is difficult to see by what other agency than a river of considerable volume and velocity the sudden introduction of such a mass of well-rounded pebbles could have been effected. It is, however, impossible to regard the Budleigh cliff section and the inland outcrops as merely portions of a river-bed filled with pebbles. The conglomerate is obviously part of an extensive stratum, and its continuation eastward has been proved by several borings, but it may not everywhere have had the same aspect as at Budleigh, and may have passed eastward into a pebbly sand.

In any case I think the Pebble Bed must be regarded as the result of some very rapid or sudden change of climatic conditions, or of a season of unusually heavy rains, which had produced floods of an almost cataclysmic character, such as sometimes occur in Persia, China, and South Africa at the present day. We can then imagine that the pebbles which had been accumulating for years in the valleys of the higher tributaries of the rivers were swept out of each valley by the swollen torrents, and were carried on by the rush of the larger rivers, to be finally spread out all over the floor of the shallow lake into which the main valleys opened.

It is evident that the rivers on the southern side of the lake were large and strong, or else that some large river entered its south-western corner, for only so can we account for the extensive spread of quartzite pebbles over the Channel floor and so far to the northward in Devonshire. The river which came in from the north and north-west through the Crowcombe valley, and carried the limestone pebbles, cannot have had so great a volume or velocity, still its flood-waters have left their record in the calcareous conglomerates of that district, and in the limestone pebbles which occur as far as Burlescombe and Collumpton.

The explanation of these pebble beds by the action of rivers in

Fig. 34.—GEOGRAPHY OF THE BUNTER EPOCH.



London : Edward Stanford, 12, 13, & 14, Long Acre, W.C.

flood naturally raises a question as to what became of the water which carried the pebbles. So much water must have greatly raised the level of the lake; but did it do more, and did it find any outlet from the lake-basin? It might be supposed that such a question could hardly be answered in the present state of our knowledge; because there is a bare possibility of its having found an outlet to the north, now concealed beneath the newer rocks of the Southern Midlands, or possibly to the S.E. under the Paris basin.

There is, however, a consideration which makes it almost certain that there was no such effluent river. The Bunter deposits of Devon are succeeded by some 1500 feet of Keuper Beds, which were clearly formed in a salt lake and certainly occupied a larger area than the Bunter Beds. If there had been a river flowing out of the Bunter lake, the valley of that river must have been enlarged by a rise in the water-level, and could not be closed except by terrestrial disturbances of an unusual kind (see *ante*, p. 211).

Consequently we may safely assume that the southern basin was an enclosed one, not only in Permian time but throughout the Triassic period; that the same rivers continued to run into it, and that the rush of fresh water which spread out the Bunter Pebble Bed was only an episode in its history. The water-level was doubtless greatly raised at the time, and the lake may have remained fresh or nearly so while some of the succeeding sandstones were being deposited, for it is quite possible that inflow and evaporation should nearly balance one another for a time, as they nearly do in the case of the modern Lake Chad.

We now pass to the Midland and Northern areas, where a more varied series of Bunter deposits has to be accounted for. So far as the Lower Mottled sandstones are concerned, they might have been formed in a large lake fed by streams flowing off a rocky desert country, from which sand was also frequently blown by strong winds into the lake. It is equally possible, however, that no such lake existed, and that the area was a desert plain, on to which sand was carried by rivers flowing from the northern mountains and from the surrounding hills; the further distribution and arrangement of this sand being accomplished by the action of the wind.

The material of both the Upper and Lower Bunter sandstones seems to have been accumulated partly by fluviatile and partly by æolian agency, and there is nothing to tell us which played the largest part in the arrangement of the deposit.

The Pebble Beds, however, afford more definite evidence, for even the strongest winds are incapable of moving more than very small pebbles, and shingle beds can only be formed on sea-coasts, on the shores of some large lakes, and in the valleys of rivers. Moreover, as we have seen, the stones themselves tell us what rocks were laid under contribution, and with a knowledge of the rocks we can discuss the probable sources from which they may have been derived.

Let us first briefly refer to the possibility of the Bunter being either wholly or partly a marine formation. This view was advocated by the late Mellard Reade, who endeavoured to show that the Pebble Beds were arranged by tidal action in the embayments of a coast-line, but beyond the fact that the deposit does lie to some extent in depressions, and that its border-line is a very irregular one, there is nothing whatever to suggest the presence of the sea or of tidal influences.

It is now generally admitted that the Pebble Beds must be either of lacustrine or of fluviatile origin. They closely resemble those of Devon, for which a semi-lacustrine origin has been suggested, but it does not follow that those of the Midland areas have been formed in precisely the same way. They differ in several respects: they do not rest on lacustrine clays but on sands; and again, the districts where the pebbles are largest are not those which are nearest to the sources from which they seem to have been mainly derived, but are, on the contrary, at a great distance from them.

Professor Bonney, writing in 1886, remarked that—

"The sandy beds of the Bunter indicate a stream flowing from one-third to half a mile an hour, the pebbles one flowing from two to three miles [an hour]. Now we must remember that in the West Central district the Lower Trias consists of three wedge-like masses about 100 miles in length, of which the coarser is probably the most extensive. The comparative uniformity of the deposits in each case indicates a uniformity of flow, and suggests either a large and broad stream, not liable to much variation, or one which, when flooded, quickly made a channel of its valley and deposited mainly at such season.

"I have the greatest difficulty in understanding how a current of the requisite velocity could be maintained by the water of a river or rivers flowing into a lake or an inland sea, or in explaining the tripartite arrangement of the beds on the hypothesis that a basin was gradually filled up from the northward by a stream which, like the Rhone at the upper end of the Lake of Geneva, gradually advanced its delta by flowing over the materials which it had previously deposited in the basin. Hence I believe that we must regard the Bunter Beds as subaerial deltas analogous to the conglomerates in the Siwalik deposits of India, and to the sandstones and Nagelflue on the outer zone of the Alps, deposits in all respects very similar to the English Bunter.

"We may suppose, then, that rivers emerging on each side of the Pennine chain from a mountain land [to the north] first formed the Lower Bunter sandstones, then, owing to increasing upheaval in the mountain district and corresponding depression in the lowlands, flowed more swiftly, so as to cover this deposit with the Pebble Beds, and, lastly, as its former conditions returned laid upon this the Upper sandstones."

In later publications he has only modified these views, in so far that he does not regard the Upper and Lower sandstones as being so entirely fluviatile as the Pebble Beds. His present opinion, as he kindly informs me, is that though much of the sand was doubtless brought down to the plains by rivers, its distribution was probably more the work of æolian than of fluviatile agencies. In particular he would regard the Bunter sandstone of the Vale of Clywd as mainly an æolian deposit, the sand having been blown off the northern plains by northerly winds, and driven up the valley, and not carried down it by any kind of water-transport.

Professor Bonney has given so much time and attention to a study of the Bunter deposits, and has such an intimate knowledge of the rocks concerned in the question, that no one is more likely to have arrived at correct conclusions on the subject. He has certainly made out a strong case for the existence of a large north-western river, receiving tributaries from the west of Scotland and from the vanished land which united Scotland to Ireland, and carrying pebbles derived from that region down into the Midland parts of England.

It is not necessary to suppose that the pebbles of quartzite and of Torridon sandstone have been carried all the way from the extreme north-west of Scotland, for pebbles of both these rocks occur ready made in the Old Red Sandstone conglomerates of Callander in Perthshire and of the Isle of Arran, and they may have existed in similar conglomerates even farther south. Still, the distance from Arran to Shropshire and North Staffordshire is over 300 miles, and the greater part of this intervening space must have been a wide and gently sloping plain.

We have, therefore, to accept the existence of a river which was capable at times of transporting large pebbles for a distance of 300 miles and more over a sandy plain. To do this it must have had a sufficient volume and velocity to be flowing at the rate of about 3 miles an hour at the end of such a long course ; but this is not an impossible feat. The plains of Piedmont and Lombardy are based upon a continuous mass of gravel, the materials of which have been brought down from the great circle of mountains which surrounds the basin of the Po ; and Professor Bonney informs me that the present bed of the Po at Piacenza is full of pebbles which have probably travelled from the Western Alps at the head of the basin, and consequently across 100 miles of plain.

A still closer parallel to the transport of the Bunter pebbles is found in the Helmand River, which flows from the mountains of Afghanistan over a vast desert plain into the salt lake of Seistan. Shingle-bars in the bed of this river are recorded by Mr. G. P. Tate [1] as far down as Jan Beg, a distance of about 200 miles from the border of the plain, while plateaus and terraces capped by gravel extend for another 40 miles to the borders of the lacustrine alluvium. The transport of these pebbles by the Helmand has doubtless been accomplished by the floods of water which are poured into its valley in the spring, when the rainfall and snowfall in Afghanistan have been greater than usual. Even in ordinary seasons the flood-waters of the Helmand flow at a rate of about 4 miles an hour at the head of its delta.

An objection of some weight has, however, been raised against the transport of the Bunter pebbles from the N.W., for if they had been carried by a river coming from that direction, the size of the pebbles should increase toward the source of supply, whereas the reverse appears to be the case. On this point Professor Bonney informs me that pebbles of a fair size are not wanting in Lancashire, for near Liverpool pebbles of 2 to 3 inches in diameter are not uncommon. Further, he thinks that in Lancashire the largest pebbles may be restricted to a single channel which is not exposed, and that when the river was in flood it distributed more sand than pebbles over the adjacent plains, while farther south-east the river may have branched out into several channels, each of which would carry its burden of pebbles, and would ultimately form a subaerial delta.

The small admixture of local rocks in the Midland Pebble Beds is, of course, easily accounted for by the occasional inflow of brooks and torrents from the surrounding tracts of high ground. But the source of the quartzite pebbles which contain Ordovician fossils of species only yet discovered in France is at present a mystery. They are not common, but they occur at many places, and they must have come from somewhere within the drainage area. They cannot have come from the south-west, for we have seen (p. 220) that the drainage of the Bristol Channel area was directed into the southern lake. It is more likely that they came from the S.E., and that such quartzites exist among the rocks of the ancient

[1] *The Frontiers of Baluchistan* (1909), Wetherby and Co.

land which is buried beneath the Neozoic strata of Suffolk, for as we have seen this land must have risen to a height of at least 2500 feet above the Bunter plain.

So far as the deposits of the Western Midlands are concerned, transport from the N.W. seems to be the only adequate explanation of the facts, and though it is not free from difficulties, it is the most probable solution of the problem. Professor Bonney, however, supposes that there was a similar river coming down through the eastern lowland and bringing a similar assortment of pebbles into South Yorkshire and Nottinghamshire. I cannot help feeling that there is far less positive evidence for the existence of such a second river. No unaltered Torridon sandstone occurs on the eastern side of Scotland, but the river might have had a tributary capable of bringing pebbles from the Sparagmite of Norway. The "Old Red" conglomerates of Eastern Scotland may also contain quartzites of exactly the same kind as those of Callander and Rothesay, but this is not yet known to be a fact.

Scotland at this time was united to Scandinavia, and the combined mass of high mountainous land must have been the gathering-ground of many rivers, large and small. Thus it is highly probable that a large river did issue from these highlands, and did flow southward over the eastern plains, but I very much question whether it curved thence to the S.W. and lost itself in the English Midlands. We have seen (p. 229) that the outlet of the whole British system of river-drainage was most probably eastward toward Denmark and Germany; consequently it is much more likely that the eastern river curved to the S.E., and never came anywhere near our present eastern counties, but emptied itself into the Germanic basin.

How, then, can we account for the pebbly sandstones of Nottinghamshire? I would suggest that they are the overflow of the N.W. river. As in the case of the Helmand and of other rivers which flow off mountain regions on to desert plains, its volume doubtless varied greatly not only at different seasons of each year, but also in different years, according to the quantity of rain and snow which fell on the catchment area of its sources. In ordinary seasons the full river may not have carried pebbles beyond the plain of the Western Midlands, losing itself in the sands with which that depression had already been filled, but occasionally its flood-waters may have risen high enough to force a way across Derbyshire into and through the eastern lowland.

The fact that the assemblage of pebbles in Nottinghamshire is substantially the same as that in Staffordshire can be easily understood if they are the deposits of one and the same river; while it is much less likely that two large rivers should bring an almost identical set of pebbles into such close apposition.

Another difficulty which is created by the theory of transport from the north is that of the existence of salt lakes at the northern end of the plains on each side of the Pennine uplift. Such lakes cannot have lain in the paths of the great rivers nor of any tributary of them. The deposits formed in them do not include Pebble Beds; consequently the streams running into them must have been small, and the surrounding slopes must have had a very small elevation above the level of the plains.

If, however, we look at the map (Fig. 30), we shall see that the evidence for the existence of the lakes is found just in the places where it is most likely that such depressions would occur, *i.e.* in the angles made by the union of the Pennine anticline with the east and west ridge of the Scottish Uplands. Depressions are very likely to have existed in these corners on each side of the broad and low anticlinal ridge, and small streams flowing into them after the rainy season would produce lakes, but might never carry any great volume of water.

When, too, we consider the great width of the area over which the Bunter sandstones appear to have extended between Ireland and the Pennine area, it is evident that there was plenty of room for several small independent drainage areas to have existed both to the east and the west of the median course, which a great river from the N.W. is likely to have taken.

2. Later Triassic Time

A. *The Keuper Deposits*

The Upper or Keuper division of the Trias has a much wider extension than the Lower, and its component beds are much less variable in their characters. From these facts we may infer that it was accumulated under conditions which secured a greater uniformity of deposition than those which governed the distribution of the Bunter sands and Pebble Beds. In the following pages some account of these Keuper deposits and their original extension, alike in England, Ireland, and Scotland, will be given.

1. **England.**—There is sometimes a certain amount of unconformity between the two divisions, the surface of the Bunter being in that case uneven and eroded, and the base of the Keuper in the Midland Counties is always a breccia, pebble bed, or conglomerate. Over this base there are red, yellow, and white sandstones, and

these are succeeded by flaggy sandstones and sandy marls passing up into red marls with beds of rock-salt and gypsum.

The Lower Keuper sandstones are generally rather soft and fine-grained, often micaceous and laminated, and frequently current-bedded. There are, however, some beds of coarser sandstone with worn and rounded grains, which may have been wind-borne sands. The red flaggy sandstones, which are generally known as "the water-stones," exhibit clear signs of having been deposited in the shallow waters of a lake. Ripple-marks, sun-cracks, rain-prints, worm-markings, and the footprints of reptiles are common on their surfaces.

The red and mottled marls are such as would be formed in the deeper parts of the lake, and they sometimes include beds of sandstone, which contain remains of plants, fish, and small crustaceans (*Estheria*). A few casts of bivalve mollusca have also been found at Shrewley in Warwickshire, but their generic affinities are doubtful.

The thin layers of sandstone in the marls are locally called *skerries*, and those of East Nottingham have recently been studied by Mr. Bernard Smith,[1] who describes them as occurring in "skerry-belts," composed of alternations of micaceous calcareous sandstone, shale, and marl; each belt being usually about six feet thick. The sandstones consist of quartz and broken dolomite crystals, both in small and even-sized grains; the layers are frequently laminated, the laminæ being often oblique or contorted and truncated by current action. With respect to the conditions under which these belts have been deposited he infers that they involved the following successive episodes:—

(*a*) "Rather shallow waters slowly becoming desiccated during a dry period; deposition of fine sediment as marl and formation of salt crystals in the upper clayey layers.

(*b*) Influx of fresh water bringing sediment. Casts taken of salt crystals now dissolved out. Formation of skerry by successive freshets of water and current action.

(*c*) As supply of coarse sediment failed laminated shales were deposited, finally passing into fine sediment as marl. Conditions repeated for every skerry."

He also points out that the characters of the Waterstones near their outcrop suggest accumulation in very shallow water, and "even that large tracts with isolated pools were laid bare from time to time." . . . "When traced eastward beneath the surface, however, the Waterstones become more like the marls above them. In a boring at Rampton they were with difficulty separated off

[1] *Geol. Mag.*, 1910, p. 302.

from the Marls, and at Lincoln their distinguishing characters are almost wholly absent, only a very little sandstone indeed being present. Thus in the east we seem to have a more open water-area which, in the first case, was probably quickly flooded so that the typical shore-line phenomena of the Waterstones were not there developed," and the conditions were continuously favourable for the deposition of marls.

The thick beds of rock-salt and gypsum which occur in the marls not only attest the saline nature of the water, but prove that there were times when the lake was so lowered and condensed by evaporation that some of the salts in solution were precipitated on the lake bottom. If it be asked why the salts were not re-dissolved when rivers again poured fresh water into the basin, two explanations may be given: (1) on some occasions it is probable that the quantity of incoming fresh water was only sufficient to check deposition, and to hold the remaining salts in solution; (2) when the rivers were full they would carry down the red mud which forms the material of the marls, so that a bed of marl would be spread far and wide over the lake floor, covering up the layer of salt or gypsum, and so protecting it from solution.

An interesting proof of the arid desert conditions which prevailed round the lacustrine areas in early Keuper time has been found in the grooved and sand-polished surfaces of granite which were buried under the Keuper marls of Charnwood Forest. The best exposure of these curiously sculptured surfaces is that in the large granite quarry at Mount Sorrel, and it has been well described by Professor Watts.[1] There is here a steep slope or face of granite exhibiting several broad and more or less deep horizontal grooves or flutings, one above another, and all with smooth and rounded outlines. These grooves were found to pass laterally behind a mass of Keuper marl, as shown in the view (Fig. 36), and are thus proved to be features engraved on the granite before the hill was buried under the deposits of the great salt lake. For the loan of the negative from which Fig. 36 was taken I am indebted to Mr. H. Meadows of Leicester.

The grooves at Mount Sorrel are not polished, but several fragments of polished granite were found embedded in the marl, and these exhibit the peculiar irregular and glazed surface which is known to be the product of sand-erosion. It is clear, therefore, that the granite was subjected to the action of wind-driven sand for a long period, perhaps during the Bunter as well as the earlier part of Keuper time; its more exposed bluffs and terraces being

[1] See *Rep. Brit. Assoc.* (1889), p. 748, and *Proc. Geol. Assoc.* vol. xvii. p. 379.

horizontally grooved and undercut exactly in the same way as rocks and buildings are eroded by the fierce sand-laden winds of Persia and Baluchistan at the present day.

The dryness of the climate throughout Keuper time is attested by the perfectly fresh and undecomposed condition of the granite where it has been covered by the Keuper marls, not only at Mount Sorrel but at other points ; this fresh condition contrasting strongly with the rough and weathered surfaces which the same rock exhibits where it has been exposed to the air since the Glacial epoch.

The Keuper deposits, like those of the Bunter, are thickest in Cheshire, where they are believed to be over 3000 feet thick. Thence they seem to thin in every direction, but most rapidly to the south and south-east. Traced through Worcestershire they thin from 1000 to 600 feet, and through Gloucester from 600 to 200 feet.

Near Bristol and round the Mendips the Keuper is partly represented by shore-beds consisting of sandstone and conglomerate, the components of which are held together by a dolomitic cement, whence it is known as the Dolomitic Conglomerate. The stones and blocks are often large and angular, so that it is generally a breccia rather than conglomerate ; the fragments consist chiefly of Carboniferous limestone, with some of Millstone Grit and Coal-measure sandstones. The deposit is seldom more than 30 feet thick at one place, but it occurs at all horizons along the margin of the formation, dovetailing outward into sandstones and marls. It is analogous to the shore breccias and conglomerates which are being formed round some islands at the present day, and there can be little doubt that the Mendips and the other tracts round which it occurs formed islands in the great inland sea or lake, even as the "Steep" and "Flat" Holmes now do in the Bristol Channel.

South of the Mendips the red marls rapidly thicken to 800 feet, and farther south in Devon the Keuper is estimated at from 800 to 1300 feet. Westward the series becomes thinner. In Monmouth and Glamorgan there are conglomerates succeeded by sandstones and magnesian limestones and red marls, overlapped northward and also southward near Cowbridge by the Rhætic and Lias ; they seem to have been formed in a narrow inlet which ran westward to and beyond Bridgend. Part of a similar tongue of Trias occurs in Somerset on the south side of the Bristol Channel, by Watchet and Minehead, and this may originally have occupied a considerable part of that space now covered by the water of the Bristol Channel.

If we proceed south-eastward from Cheshire, we find the Keuper diminishing to about 1000 feet in South Staffordshire, and to about 700 feet in Warwickshire; while borings near Northampton disclose the very eastern limits of the formation, its thickness there varying from 24 to 82 feet.[1] The Gayton boring is especially interesting, for beneath 60 feet of red Keuper marl and sandstone 13 feet of breccia was found, consisting of large blocks of Carboniferous limestone and sandstone embedded in a sandy matrix. Under it were 9½ feet of marl and shale, which rested on an eroded surface of a limestone belonging to the Lower Carboniferous series. Such a breccia can only have been formed in close proximity to a shore-line, and the blocks are probably the débris of a cliff that overhung the waters of the Keuper lake.

Charnwood Forest was an island in this inland sea, for the Keuper sandstones thin out against the lower slopes of the Charnian rocks, and are overlapped by the red and grey marls, which fill the ancient valleys and mantle the slopes of the buried hills. An excellent description of the physical features of this district and of the curious manner in which they have been developed has been given by Professor Watts.[2] From this I quote the following paragraph:—

"Thus the New Red Marl is actually covering a mountain system of which the summits alone are visible, while the flanks and intervening valleys are for the most part buried and filled up with the newer formation. Areas like the granite knobs of Mount Sorrel, the copse-clad crags of Bradgate Park, or the isolated rocks in the centre of the Forest about the headwaters of the Blackbrook, give examples of innumerable summits, from a tenth of a square mile to 100 square yards and less in area, standing forth like islands from a sea of Marl."

Rain and streams are now engaged in gradually removing this mantle of marl from the peaks and slopes of the ancient hills, and are slowly revealing the features which had existed in Triassic time. "It is indeed," as Professor Watts says, "a Triassic landscape which is now being uncovered again or *developed* for our inspection, and we are at liberty to use it to picture to our minds the appearance of this part of England in Triassic times."

The only comment I would make on the above description is that the Charnwood Hills can hardly be said to form a "mountain system," unless the words *in miniature* be added, for only one summit rises to as much as 900 feet above the present level of the sea, and the average elevation of the hills above the base of the Keuper sandstone cannot be much more than 800 feet. A boring near Leicester, begun about 40 feet below the top of the Trias,

[1] *Quart. Journ. Geol. Soc.* vol. xl. p. 482.
[2] "A Buried Triassic Landscape," *Geog. Journ.*, 1903 (June).

Photo *Mr. F. G. Collins, F.G.S.*

Fig. 35.—PERMIAN BRECCIA TRAVERSED BY THE RAILWAY NEAR IDE, S.W. OF EXETER.

Photo *H. Meadows.*

Fig. 36.—VIEW OF SAND-WORN GRANITE BENEATH TRIAS IN MOUNT SORREL QUARRY.

traversed 700 feet of red marl and 100 feet of red sandstone, reaching slaty rock at 800 feet.

South of Warwick the Keuper marls and sandstones are known to extend beneath Oxfordshire, a boring at Burford proving them to be there 428 feet thick, and it is probable that they stretch continuously below Berkshire, Wiltshire, Dorset, and Hampshire, and under the floor of the English Channel for a considerable distance. A boring at Lyme Regis traversed 1156 feet of the Red Marl series without reaching the basal sandstones, which are 75 feet thick at Sidmouth; so the total thickness of Keuper is more than 1200 feet.

With regard to the red rocks which have been proved by borings to exist below Richmond, Kentish Town, and Crossness, I have already given reasons for believing them to be of Palæozoic age (see p. 107).

Another strong objection to the view that any of them belong to the Trias is the fact that they are not covered by Lias, but by Great Oolite. The Keuper marls are almost always succeeded by the Rhætic and Liassic Beds, and it is not probable that these beds would be entirely unrepresented at Richmond if the red rocks belonged to the Keuper. This argument has been strengthened by the discovery of both Lias and Trias at Brabourne in Kent, between Canterbury and Dover. A boring there traversed both Middle and Lower Lias (thickness 172 feet), below which are red and grey sandy marls, with a coarse dolomitic conglomerate containing pebbles of Carboniferous limestone; these beds, which are only 48 feet thick, certainly seem to be of Triassic age, and they rest on hard (? Devonian) slate.

This boring at Brabourne appears to have struck a Triassic valley which drained westward into the Keuper lake, and was invaded by the lake waters at the close of Triassic time, not long before the invasion of the lake basin by the Liassic sea. That the Trias lies in a valley at Brabourne is shown by the fact that in all the other deep borings in Kent the beds which rest on the Coal-measures are referable to the Lias, and apparently to the Middle or Upper Lias, for they are everywhere very thin, from 15 to 54 feet.

No Trias or Lias has been found in the Boulonnais, but a coarse dolomitic conglomerate with boulders of Devonian and Carboniferous rocks was traversed by a mine-shaft at Rocourt near Douai, and conglomerates of rolled pebbles in a red magnesian matrix occur near Pernes, Flechin, Febvin, and Audichthun; these are probably all valley-deposits of Triassic age, but there are no red marls nor any indication of lacustrine deposits.

The only evidence hitherto adduced for the existence of Trias in the northern part of the Paris basin is that of a boring at Merlimont, near Etaples, south of Boulogne. This boring has been recorded by Professor Gosselet;[1] after traversing the Chalk and a bed of variegated clay with Gault fossils it entered hard red and grey sandstones (22 feet), below which were beds of hard greenish quartzite with bands of decomposed shale and sandstone. Professor Gosselet refers the upper 22 feet of sandstone to the Trias, apparently because of their colour, and because of a rather coarser texture, but these reasons are quite insufficient. No pebbles or other signs of unconformity were found in their lowest bed, which is described as a red argillaceous sandstone with grey veins; this rests directly on quartzite, red sandstone, and red and green clay, all of which are referred to the Devonian.

To draw a line at the top of the quartzite, as separating the Devonian from a member of the Trias, seems to me a very strained interpretation of the facts, for the redness and less compact texture of the upper beds are likely to be due to weathering prior to the deposition of the Gault, and I see no reason why the whole series should not be referred to the Devonian.

Professor Cayeux has assured me that this boring is the only one between Paris and the northern coast which has been carried deep enough to reach either Lias or Trias. He informs me, however, that the Lias was reached in a boring made at Rouen in 1906, which passed through 12 metres of Upper Lias; but a boring at Havre found Silurian rocks directly below the Great Oolite, so that the Lias of Rouen is at present an isolated fact, and by no means involves the occurrence of Trias in this part of France. There is then no reason for supposing that there was any connection between the lake of the English Keuper and the area of deposition in the east of France and Lorraine.

How far the Keuper marls extended originally to the west of the Midland Counties is a difficult question. That they overlapped the Bunter is fairly certain, because they do so in all other directions. It is, of course, easy to replace the thickness of the Keuper Beds which have been removed from the surface of the Bunter in Worcester and Shropshire, but when we reach the Palæozoic rocks we cannot prolong the plain of the Trias indefinitely, because the present surface of West Salop and Hereford must be very different from the surface which existed there in Triassic times.

In Worcestershire, Shropshire, and Cheshire the basement-bed of the Keuper is very often a breccia, and the angular fragments of which such a rock consists cannot have travelled far; hence it

[1] *Ann. Soc. Géol. Nord*, tom. xxxii. p. 138 (1903).

is clear that mountains and rocky slopes still existed to the westward, as they had done during the preceding Bunter and Permian epochs. It is fairly certain, therefore, that when the Midland area was invaded by the waters of the Keuper lake, the western shore of this lake corresponded very closely with the border of the Bunter sandstone plain, and did not encroach far on the steep slopes of the Western Highlands. As time went on, and when some 3000 feet of red sandstone and marl had been deposited, the lake-waters must have covered more than that amount in vertical height, but how far west such an alteration of level would carry them we have no means of knowing.

In the N.E. of England the Keuper sandstones are not very thick, but they present some interesting features. Near Nottingham there is a well-marked basement-bed of breccia, conglomerate, or white sand succeeded by a variable set of red and green sandstones; but farther north the signs of erosion disappear, and no break is perceptible at the base of the Keuper, while in Yorkshire, north of Ripon, there is such complete similarity and continuity between Bunter and Keuper that no line of separation can be drawn between them.

The whole series is truncated by the coast of the North Sea at Teesmouth (see Fig. 30), and it may safely be assumed that the Keuper extends far to the eastward under the North Sea toward Denmark, and also that it originally spread north-eastward over the Magnesian limestone into the northern part of the same sea, but how far we do not know.

Here we may pause to consider how far the Keuper marls are likely to have extended over the central and southern parts of the Pennine chain. This is not an easy question to answer, because the complete history of the Pennine area has not yet been worked out. We have seen that in the Eden valley the Pennine faults are largely of pre-Permian age, but that there were also movements of post-Permian date. Some of these latter may be pre-Triassic and some post-Jurassic; the great faults near Preston in Lancashire are certainly post-Triassic, and probably date from Cretaceous or Tertiary times.

We have, however, a basis of calculation in the Permian outlier which lies on the Ingleton coalfield, and is scarcely affected by the Ingleton and Settle fault. There can be no doubt that the Permian sandstones covered the whole Ingleton district up to a certain level, and were overlain by a considerable thickness of Trias; further, since it lies nearer to the Triassic area of Preston than to that of the Appleby district, we may assume that the Lancashire series was prolonged over it. In North Lancashire the thickness of the Bunter is about 1300 feet, but that of the Keuper is unknown, because much of it lies below the sea; there is probably 200 feet of Keuper sandstone, and the marls can hardly be less than 1500 feet and may be 2000. Even if we allow for some easterly thinning of the beds we shall probably be under the mark in assuming the Triassic cover of the Permian outlier to have been 2500 feet.

The height of the present surface of the outlier is about 1000 feet, and we may allow for another 200 feet of Permian, so that we get a total of 3700 feet above sea-level for the upper surface of the Keuper marls. This is a much greater height than any of the neighbouring hills; Ingleborough and Whernside both rise to over 2300 feet, but none of the country round Settle or that between Burnley, Keighley, and Leeds rises to more than 1800 feet (see Fig. 30). Consequently it seems likely that some of the Keuper marls did pass over this area.

We may check the above by prolonging the dip and thickness of the eastern Trias for a certain distance westward toward the central axis of the Pennine range. Thus in Yorkshire between Thirsk and Wath, a distance of 8 miles, the Trias is about 1500 feet thick, and is nearly at sea-level; and from Wath to Whernside is 20 miles, which with the same dip will bring the basal plane to 3700 feet and the upper surface of the Keuper to 5200 feet above the sea.

It is true that we must allow for a certain amount of denudation, but if the Keuper passed across the Palæozoic ridges then the greater part of the Jurassic series must also have done so, and the Palæozoic floor would have been covered by some 3000 to 4000 feet of Trias, Lias, and Oolites. Some of this was doubtless removed in late Jurassic and early Cretaceous times, but it is not likely that much of it was destroyed before it again sank beneath the Cretaceous sea and received a further covering of deposit. In Eocene time it was again brought above the sea-level, and since then detritive agents have been continuously at work upon it, but before the surface of the Palæozoic rocks was exposed they would have to clear away the Chalk and all the underlying Jurassic and Triassic deposits. It seems very probable, therefore, that the pre-Triassic surface of the older rocks was not many hundred feet above the highest points of the present surface. Even supposing it was 1000 feet above the present summit of Whernside, it would not reach the level to which a prolongation of the eastern dip brings the base of the Bunter.

These calculations and surmises, however, only apply to the area of Yorkshire and North Lancashire, and it does not follow that the Derbyshire heights were similarly submerged and buried beneath Triassic and Jurassic deposits. The latter must be considered separately, but it so happens that another line of reasoning can be brought to bear on the southern part of the Pennine range. The broad Derbyshire anticline lies between two equally deep and broad synclines, and the manner in which both Trias and Lias come into these basins makes it almost certain that they both dipped off the intervening anticline ; in other words, the final arching of the anticline was completed by post-Jurassic flexuring.

The western side of the arch is broken by a fault of considerable magnitude, whereby the Trias is depressed below its original relative level, but we can use the dip of the beds on the eastern side as a means of estimating how much of the Trias did pass of the central heights. The thickness of the Trias on the borders of Nottingham and Yorkshire has been ascertained by borings at Haxey, near South Carr, and at Scunthorpe, the former traversing 438 feet of Bunter and the latter showing the Keuper sandstones to be about 660 feet and the Keuper marls to be 862 feet; so that the total thickness of Trias is here also about 1960 feet, and the whole area is very little above sea-level.

If now we draw a section from Gainsborough to the Peak of Derbyshire through Sheffield, continuing the dip above indicated for half the distance and then lessening it to half the amount, so as to allow for the arching of the anticline, we shall get the approximate position of the base of the Trias over the summit of the anticline. The distance across the Trias is 15 miles, and we have seen that the dip brings in 1960 feet. From the Trias boundary to the western end of the Peak plateau is a distance of about 28 miles ; the same dip for 14 miles would take the base to 1800 feet above the sea, and by depressing the angle by half for the remaining 14 miles we should carry it to 2700 feet. This is considerably above the present height of the Peak, which is about 2000 feet, but we must allow for post-Cretaceous detrition ; hence it would appear from this rough calculation that the Bunter may have thinned out against the ridge, but that most of the Keuper passed over it.

This conclusion seems to accord with the known stratigraphical facts, for round Derby and Ashbourn, where the Pennine axis passes below the Trias, the Bunter is reduced to a small thickness (about 100 feet), and the Keuper sandstones thin out entirely. Hence it is probable that farther north, and in fact along the whole Pennine ridge, only the Keuper marls passed completely over the Carboniferous rocks.

Passing now to glance briefly at the more northerly areas of deposition, we find a similar Keuper series, consisting of sandstones succeeded by red marls with beds of rock-salt and gypsum in the Carlisle basin, and also below the northern part of the Isle of Man ; and there can be little doubt that it originally spread over the whole of the Lake District (see p. 226). Similar beds are also found in Antrim, from the southern end of Lough Neagh to Cushendall on the N.E. coast, so that it is evident the great salt-lake stretched across the Irish Sea and some distance into the N.E. of Ireland.

2. Scotland.—Rocks of Triassic age are found in several parts of Scotland, and are probably for the most part referable to the Keuper division. Beds which have a general similarity to the Cumberland series occupy the southern part of the Isle of Arran, where their relative age has been determined by the discovery of a Tertiary volcanic vent and of a volcanic agglomerate, including large masses of the sedimentary rocks by which the volcano was surrounded at the time of eruption. One of these masses comprises Rhætic shales, with grey and red marls in descending succession. In Brodick Bay red marls and shales with calcareous concretions pass down into soft red sandstone, and lower still are alternating beds of sandstone and conglomerate. Between Brodick Castle and Corrie these conglomerates overlie bright red sandstones, with conspicuous current-bedding, and at least 1000 feet thick.[1] In some parts of the island these lowest beds are absent, and the conglomerates rest on the Carboniferous limestone. The lower beds greatly resemble the Penrith sandstone, but there does not seem to be any break betweeen them and the conglomerates.

Triassic rocks of a rather different type are found still farther north on both sides of Mull, and on the adjacent coast of Argyle, in the Isles of Skye and Raasay, and in the cliffs of Gruinard Bay (Ross-shire). The beds are variable in character, and have evidently been accumulated under special local conditions. According to Professor Judd[2] the Trias of this region, where most fully developed, is divisible into three parts of different lithological character. These are, in ascending order : (1) breccias, conglomerates, and sandstones, varying in thickness from 60 to 500 feet ; (2) red clays and marls, with beds of concretionary limestone, from 20 to 200 feet ; (3) sandy shales and sandstones, often white or greenish, with a thickness of 50 to 200 feet, but only found at the more northern localities.

In the peninsula of Gribun in Mull the basement-bed, resting on Archæan rocks, is a breccia passing up into a coarse conglomerate,

[1] *Sum. Prog. Geol. Survey* for 1896, p. 66 ; and for 1898, p. 133.

[2] *Quart. Journn. Geol. Soc.* vol. xxxiv. p. 686 *et seq.* (1878).

over which is a mass of alternating and irregular beds of conglomerate and sandstone, succeeded by greenish sandstones with beds of concretionary limestone and occasional layers of marl and of gypsum. This section is important because of the occurrence of gypsum, which has not been noticed elsewhere, nor has any rock-salt been seen. A similar series is found in Morvern, and is there from 400 to 500 feet thick, and is conformably succeeded by Lias limestone, with passage beds which may be of Rhætic age between.

In Skye the group is very thin, and in Raasay it is not much over 200 feet, but in Gruinard Bay there is at least 1000 feet of Trias, the highest part consisting of greenish and white sandstones, hard and calcareous, with intercalated bands of red sandy shale in the lower part. As the highest beds are succeeded by Lias at several places it is clear that the greater part, and probably the whole, of the series belongs to the Keuper division.

From the prevalence of sandstones and conglomerates, both in the lower and upper parts, we must infer that many rapid streams ran into the lake, while the red marls and clays indicate an episode of lesser rainfall, when the streams only carried fine mud, and when the lake-water became salt enough from evaporation to allow of the occasional precipitation of gypsum.

These remnants of Triassic deposits are buried beneath tracts of Jurassic and Cretaceous strata, which are covered by immense masses of Tertiary lavas, the whole having apparently been let down into a series of faulted troughs on the west side of the Highlands. A striking example of the displacements to which the Secondary and Tertiary rocks of this region have been subjected is afforded by the Innimore of Ardtornish on the Sound of Mull, where they are cut off against a mountain mass of Moine schist by a fault which must have a throw of about 2000 feet.

It is not surprising that Professor Judd protested against any weight being allowed to negative evidence in such a case, or that, in reference to the Trias, he remarked: "We cannot but feel that it is impossible to limit the former extent of this formation to the particular regions wherein traces of it have been accidentally preserved, or to avoid the conclusion that wide areas, now exhibiting no traces of deposits of this age, were once buried under hundreds or even thousands of feet of the Poikilitic Beds" (*op. cit.* p. 695).

Moreover, it is not only on the western side of Scotland that rocks of Triassic age have been found: they occur at Spynie and Lossiemouth in Elgin, and also near Golspie in Sutherland. As recently restricted by Mr. D. M. S. Watson (*Geol. Mag.*, 1909, p. 102), the Trias of Moray is a fine, soft, nearly white sandstone, without any distinct bedding; the base is nowhere seen, but the mass is more than 100 feet thick, and is believed to be overlain at Stotfield by a peculiar siliceous cherty rock. This rock occurs again on the other side of the Forth, below Dunrobin Castle, where it clearly overlies 40 feet of similar whitish sandstone, and is itself succeeded by a set of sandstones and conglomerates, which may be of Rhætic age, since they pass up into Lias. Hence the sandstone is of Upper Keuper age.

B. *Physical Geography of the Keuper.*

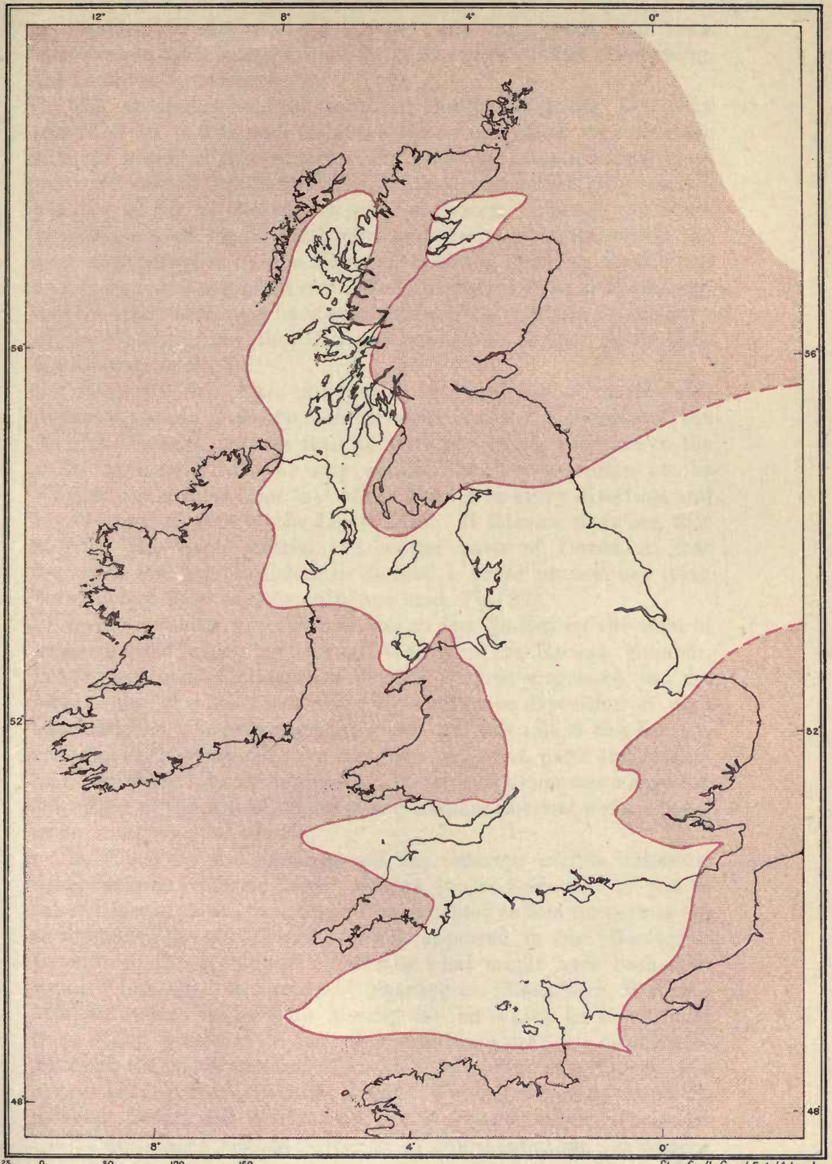
It will be remembered that in Germany the Bunter and the Keuper are separated by a series of marine beds, chiefly limestones, known as the Muschelkalk; and that this series extends to Heligoland, but is not represented in England, so that the Muschelkalk sea cannot have reached so far westward. The original elevation of the British region above sea-level must either have been greater than that of the Germanic region, or there must have been a subsidence of Central Europe in which our region did not participate. The consequence was that desert conditions continued to prevail in the British area, while marine deposits were formed in Germany.

At length, however, another change took place in the physical geography of Central Europe, and we may suppose this to have been caused by some uplift of the Alpine region, whereby the communication of the Germanic sea with that of Southern Europe was interrupted. There may have been at the same time some subsidence of the North Germanic and North Sea area. At any rate, this area became isolated from the open sea and converted into an area of great lakes, which finally became united into a large inland sea.

The geographical conditions of Northern Europe at this time have been compared to those which now exist in Central Asia, where from the Caspian Sea eastward for about 3000 miles there is a comparatively rainless region, in which all the lakes are salt, except those which have an outlet and drain into some lower lake.

We must now confine our view to the British region, and consider the effects which were therein produced by these changes. The subsidence and consequent creation of large water-spaces seem to have modified the continental conditions which had prevailed, and to have caused a greater annual rainfall, so that more or less permanent lakes were also established within the British area, though they were still surrounded by deserts, and the evaporation was often greater than the supply of fresh water. At first there were two if not three separate lacustrine areas, and it was not till

Fig. 37.—GEOGRAPHY OF THE KEUPER EPOCH.



London: Edward Stanford, 12, 13, & 14, Long Acre, W.C.

a considerable thickness of Keuper sand and marl had been deposited in them that the water-level rose high enough to submerge the intervening barrier-ridges.

The limitation of the southern Keuper deposits has been discussed on p. 242, and from the facts there stated we may infer that the waters of this southern lake gradually extended themselves eastward beyond the limits of the Bunter deposits until they reached perhaps as far as the eastern end of Sussex. Thence the shore probably curved round southward and westward again within the area now occupied by the Channel, without touching French soil anywhere to the east of Havre. We know that it entered Normandy, and the lake-waters may have covered the whole northern promontory of the Cotentin, but they did not pass much farther south than the latitude of St. Lo.

Westward this lake must have extended for a considerable distance, passing probably through what is now the opening of the English Channel, but was then an inlet narrowing westward to the valley of a river; for we may assume that the extension of the Keuper was greater than that of the Bunter in every direction, and nearly equal to that of the Lower Lias. It follows, therefore, that it must also have covered the central parts of Devon, so that Dartmoor and the Cornish hills formed a broad promontory lying between two deep bays or gulfs (see map, Fig. 37).

On its northern side the lake was at first limited by the tract of higher ground which lay between Wales and the Eastern Uplands, but as the general subsidence of Western Europe progressed, and the level of the lake floors was raised by continuous deposition of sand and marl, the lake waters gradually rose on each side of this barrier, creeping up its sides till they met over its lowest parts and formed one continuous lake or inland sea. When this union was completed the ridges of the Bristol, Mendip, and Exmoor districts were reduced to an archipelago of islands.

By following the contours and the outcrops of the dolomitic conglomerate, Professor Lloyd Morgan has endeavoured to restore the outlines of these islands, and I am indebted to him for permission to reproduce the map (Fig. 38) which appeared in his "Geological Reverie on the Mendips." Picturing what might have been seen by an "intelligent Microlestes" standing on Blackdown, Professor Morgan writes: "The main Mendip isle on which he stood must have ended westward in two promontories, a deep bay running in between, the more southerly of which, now Wavering Down, was almost isolated from the main island. Further westward Banwell, Bleadon, Brean, and Worle stood out as separate islets. Eastward the Mendip Isle stretched farther in all probability than the present

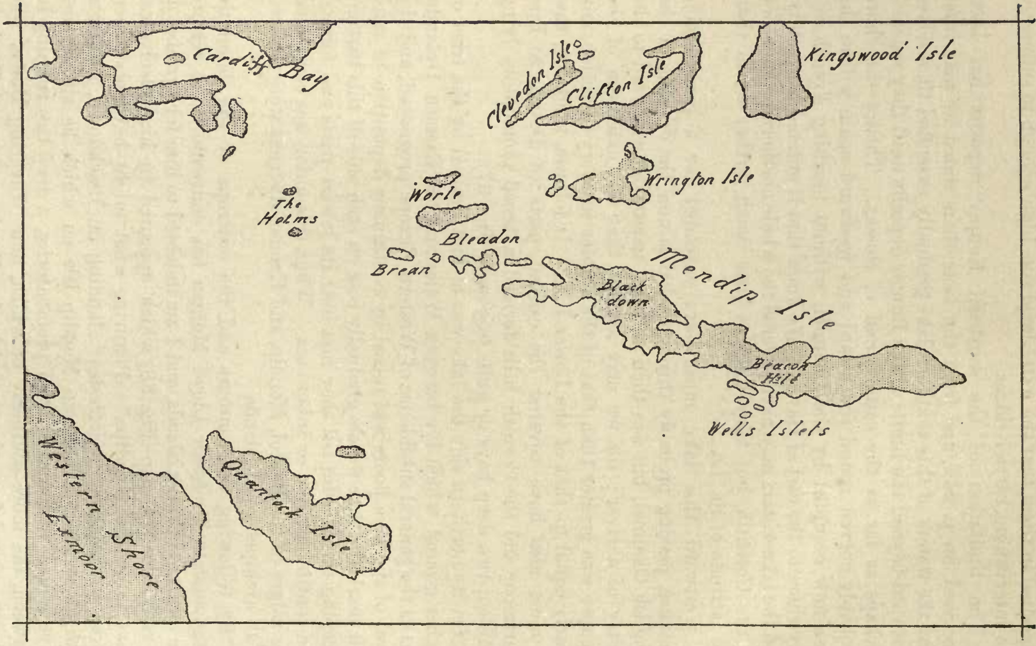


Fig. 38.—MAP OF ISLANDS IN THE KEUPER LAKE (Prof. L. Morgan).

extension of the range of hills. Northwards our Microlestes would have seen the low island of Wrington, and beyond it the long Clevedon and Clifton isles. Kingswood probably formed a Coal-measure island east of the present site of Bristol. . . . Away to the south-west he would have seen another large island, the Quantock Isle, and beyond that the western shore of the lake rising into high ground on Exmoor."

Moreover, Professors Morgan and Reynolds have pointed out [1]

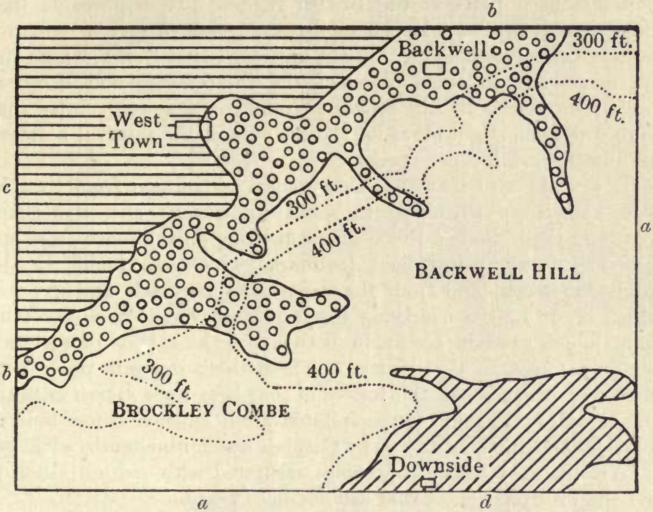


Fig. 39.—GEOLOGICAL MAP OF BACKWELL HILL BETWEEN BRISTOL AND WRINGTON. Scale 1½ inch to a mile.

d. Lias. *b.* Dolomitic Conglomerate.
c. Keuper. *a.* Carboniferous Limestone.

that, in spite of the subsequent planation of these islands by the Jurassic sea, some of their Permian and Triassic features are still indicated by the manner in which tongues of the Dolomitic Conglomerate (see p. 239) run up into the Limestone uplands.

This is exemplified in Fig. 39, for the use of which I am indebted to the authors and the Council of the Bristol Naturalists Society. It shows the manner in which the marginal Triassic deposits run up the slopes of Backwell Hill, along the lines of old valleys which formed creeks as they sank beneath the encroaching waters of the Keuper lake ; while at the same time it is evident

[1] *Proc. Bristol Nat. Soc.*, 4th ser. vol. ii. p. 5 (1909).

that the modern gorge of Brockley Combe (indicated by the contour line) is the product of a much later erosion.

Backwell Hill and the other uplands of the Wrington and Mendip islands were doubtless at this time much loftier and more rugged than they now appear, and were trenched by deep valleys along which the stones and boulders had been carried by the torrents that resulted from occasional heavy rains.

Meantime a similar sequence of events was taking place in the more northern parts of the British region. It is probable that there were at first two lacustrine areas, an eastern and a western; for the Keuper sandstones thin out entirely round Derby, where the red marls rest in some places on the Bunter Beds and in others directly on Carboniferous rocks. We may consequently infer that there was some slight elevation of this area in the interval between the Bunter and Keuper epochs.

It is clear also that the lakes varied in volume from time to time, sometimes shrinking to small dimensions and sometimes enlarging their limits; this conclusion being an inference from the sun-cracks, rain-prints, and footmarks which are found in the Sandstone series, and from the deposits of rock-salt and gypsum which occur in the overlying marls. Moreover, it is noteworthy that, though gypsum occurs in both areas, thick beds of rock-salt are only found in the western. These thick deposits prove that there were times when the waters of that lake were almost entirely evaporated, for gypsum is precipitated from solution before sodium chloride, and in the case of the Caspian water nine-tenths of it has to be evaporated before it becomes saturated with sodium chloride and the precipitation of that salt becomes possible.

In the eastern area (Leicester, Nottingham, and Yorkshire) no beds of rock-salt have been found in the Keuper series, only casts and pseudomorphs of that substance, which were probably formed in pools and lagoons along the border of that lake. We may infer from this that though evaporation often proceeded far enough in this basin to cause the precipitation of sulphate of lime, it never went far enough to produce a large area of concentrated brine from which beds of rock-salt could be formed.

The physical aspect of Central England at this time must have resembled that of the country round the Caspian, and that near the Dead Sea at the present day. Fig. 40, which has been drawn from a photograph and represents part of the Dead Sea, might well be taken as a view of the eastern Keuper lake looking westward to the southern part of the Pennine range.

In course of time, however, the floors of both lakes became so far raised by the deposition of sand and clay that the level of

Fig. 40.—VIEW OF PART OF THE SHORE OF THE DEAD SEA

the water was also gradually raised, and eventually the two lakes became merged into one, not only by union across Derbyshire and Staffordshire, but probably also across the whole of the Southern and Central Pennine area (see pp. 244 and 245).

Passing now to the northern extremity of the western area we have seen that Keuper marls occur in the Carlisle basin, and again in Arran, and it is quite possible that they were originally continuous across the whole south-western part of Scotland, though I have not ventured to show such an extension of the lake-area on the map (Fig. 37), because of the uncertainty which still exists with regard to the age of the New Red Sandstones of this part of Scotland.

Finally, we come to the most northerly areas of deposition, that on the west coast and that on the N.E. side of the Scottish Highlands. In the last edition of this book I suggested that these were both separate and freshwater lakes, the eastern discharging itself into the western by a river along the course of the "Great Glen," and the western having also an outflowing river which ran southward into the great salt lake.

At that time, however, the age of the red marls in Arran had not been determined, and I also overlooked the fact that gypsum had been found in the marls of Inch Kenneth, off the Isle of Mull, making it fairly certain that there were times at any rate when the waters of the western basin became saline. The distance between the north end of the Isle of Arran and the centre of Mull is about 60 miles, and it is of course possible that the northern area was a separate basin, but there is really no strong evidence to support such a view.

The bivalves found at Ardtornish may or may not belong to the genus *Cyrena* ; they are casts, and too obscure for accurate determination. The prevalence of conglomerates and the local character of the materials are characters which are just as compatible with deposition in a narrow arm or prolongation of the southern lake as with accumulation in a separate basin. On the whole it seems more likely that this western area was a northern gulf of the great salt lake. At the same time it is probable that the waters of the main lake did not reach so far north until the latter part of Keuper time.

With regard to the eastern area in Sutherland and Elgin the base is different. It is true that we do not know what beds lie below the whitish sandstones which are the only deposits there exposed, but so far as these are concerned there is some reason for believing them to be freshwater deposits.

One of the most interesting features of the Lossiemouth sandstone is its Reptilian fauna. This is quite distinct from that of the adjacent Permian Beds, and no fewer than eight species of reptiles belonging to as many different genera have been described from the bones found in the quarries. Teeth of the fish *Ceratodus* also occur, and most of the reptiles have a dentition which fitted them to feed on fish, but the *Hyperodapedon*, like its modern congener *Sphenodon*, may have fed on insects and other small fry.

In any case the lake in which these sandstones were formed must have afforded an abundant supply of food and drinking-water; consequently its waters are not likely to have been salt. Whether its outlet was to the westward or the eastward we have no means of deciding, but it is at any rate very likely that the outflowing stream was a feeder of the western lake.

Our view of British geography near the close of Triassic time would not be complete without a few words on the question of the eastern extension of the great lake. Was it confined to the British region, or was it united to the similar inland sea which occupied so large an area in the Baltic and Germanic regions?

The similarity not only of the Keuper, but of the Rhætic and Liassic, deposits in Hanover to the corresponding beds in England makes it highly probable that all these deposits were originally continuous across the North Sea. Again, seeing that the Keuper has a wider extension than the Muschelkalk, and that the latter occurs in Heligoland, it is nearly certain that the Keuper originally passed over that island and extended far westward across the North Sea. We may therefore infer that at some date in Keuper time the British and Germanic lakes became merged into one great inland sea.

CHAPTER X

THE JURASSIC PERIOD

The Jurassic strata, comprising the Lias and the Oolitic series, succeed the Triassic marls with complete conformity, the passage from one system to the other being through a group of grey marls, shales, and limestones which are known as the Rhætic or Penarth Beds. The Jurassic system is divisible into three rock groups or series.

The Lower or Liassic series is essentially a clay formation, with occasional bands of limestone, sand, and ironstone of variable thickness.

The Middle Jurassic series consists mainly of limestones, with only subordinate bands of sand and clay.

The Upper Jurassic, again, is an argillaceous series, the limestones being discontinuous, and sometimes absent or replaced by clays.

The most persistent formations are the three great clays: the Lower Lias, the Oxford, and the Kimeridge Clays. These range all across England, and form broad tracts of low-lying land; while the intermediate limestones, where they are well developed, form long ridges, with escarpments facing the west or north-west, in consequence of the prevalent easterly dip.

As the conditions of deposition varied from time to time, and as each of the groups above mentioned forms a record of some more or less important change in the physical geography of the British region, it will be convenient to treat each of them separately, in the same manner as we dealt with the two great divisions of the Trias.

1. Rhætic and Liassic Times

A. *Stratigraphical Evidence.*

The Rhætic Beds, though in Britain they are quite a subordinate division, and are seldom more than 30 or 40 feet thick, are of special interest because they mark the epoch when the great Triassic lake was first invaded by the sea. At or near the base of the Rhætic shales there is usually a layer of shaly sandstone, which contains phosphatic nodules and is crowded with the remains of fish and small reptiles, and sometimes there are several such layers. It would appear that the highly saline and bitter waters of the Triassic lake were prejudicial to the fish and other creatures which were carried into it by the first irruption of the outer Rhætic sea; so that most of them died, and their bones, scales, and teeth were drifted into layers on the sea-floor.

Rhætic Beds, having the same general aspect and similar small thickness, have been found everywhere in England and Ireland where the Lias reposes on the Trias. Black shales with Rhætic fossils have also been found in the Isle of Arran. Farther north, however, the passage beds between the two formations have a different facies; thus in Skye they consist of thin limestones, calcareous sandstones, and shales which only contain a few obscure fossils of marine genera. Similar passage beds occur in Raasay, where they contain species of *Modiola* and *Pleuromya.* The fossils are therefore sufficient to prove that these beds are marine deposits, and they are probably of Rhætic age.

In Glamorganshire also the Rhætic Beds change westward from the normal into a littoral facies. At Penarth, south of Cardiff, they consist of black shales overlain by thin white limestones (the White Lias), but between Cowbridge and Cardiff these give place to white and green sandstones, overlain sometimes by shelly sandstones, sometimes by red and green marls, which resemble those of the Keuper, and seem to have been formed in a salt lagoon [1] on the border of the sea.

The Lias is a much more important formation, and its full thickness is about 1000 feet. It is divisible into Lower, Middle, and Upper stages, of which the lower is generally the thickest. The broad outcrop of the Lias stretches across England from Dorset to Yorkshire, and outlying tracts occur in Staffordshire, Shropshire, and Cumberland, and in the north-east of Ireland. Lias occurs also in Arran and on both sides of the Scottish Highlands. The thick clays and shales of this series indicate a sea into which many rivers discharged a constant supply of muddy material derived from the waste of the surrounding land. The dark-grey shaly beds, which are familiar to us under the name of Lias, with the frequent interbedded layers of argillaceous limestone, are evidently deposits formed in the more central and deeper parts of the sea; and there are only a few localities where

[1] See *Sum. Prog. Geol. Surv.* for 1899, p. 131.

shore deposits of the same age have been preserved, but of these we shall take special notice.

The area covered by the Lias was practically the same as that occupied by the uppermost Keuper marls, but the continued subsidence carried even the Lower Lias somewhat beyond the limits of the inland sea. This extension of the area covered by water was of course greatest where the bordering land was lowest, and was least where the slopes were steep, as they probably were on the Welsh side of the sea. Here and there we have evidence of this overlap of the Trias by the Lias, and it will be our first endeavour to indicate the approximate boundaries of the Liassic sea in the British region.

It will be convenient to begin on the eastern side, where the highland described in the last chapter stretched across the North Sea from Belgium to our eastern counties. The western coast of this land was probably steep and rocky, consisting as it did of the hard Palæozoic rocks which borings have proved to exist below the counties of Suffolk, Hertford, Middlesex, and Surrey.

At and near Northampton, where the Trias is only from 24 to 82 feet thick, the Lias has a thickness of about 720 feet, which probably carries it some 30 or 40 miles farther east, unless the slope of the eastern land was very steep in that direction. Thus it is probable that Lias would be found under St. Neots, and perhaps under Cambridge; but east of the latter place there must be a rapid thinning out of beds against the slope of the Palæozoic floor, for a boring at Culford, north-east of Newmarket, found Palæozoic rock at the small depth of 638 feet from the surface, and directly below the Cretaceous deposits. Consequently, if any Jurassic Beds spread over Suffolk they must all have been destroyed during the Purbeck-Wealden interval. Some of the Upper Jurassic series may have had such an extension, but it is not likely that any part of the Lias reached so far to the east along this line of latitude, though it doubtless follows the Keuper under the North Sea outside Norfolk.

Farther south, in Oxfordshire, a boring at Burford passed through 650 feet of Lias, and eastward it probably thins out in the same way, so that its shore-line may lie somewhere under the Chiltern Hills, but no borings in that area have yet gone deep enough to afford evidence of this. The theoretical and diagrammatic section, Fig. 41, illustrates the manner in which the whole Jurassic series is believed to thin out eastward below the Cretaceous strata, which rest directly on the Palæozoic at Ware in Hertfordshire. A part of this overlap has actually been proved by borings near London; thus at Richmond both Trias and Lias are absent, and the Great Oolite rests directly on the Palæozoic platform. Still farther south, however, the Lias comes in again on the southern flank of the old land-surface and has been proved by several borings in Kent. Thus at Brabourne near Ashford a thickness of 172 feet of Lias was found above the Triassic Beds mentioned on p. 241, 97 feet of this being referred to the Lower and 75 to the Middle Lias. Farther east the Lias overlaps the Trias in all directions ; thus at Ellinge near Swingfield there is only 54 feet of Lias lying directly on Coal-measures, and near Dover it is reduced to 37 feet. In the Ropersole boring, near Barham, only 27 feet of Lias was found, and at Waldershare, north of Dover, there is only 5 feet.

No Lias has been found in the Boulonnais, so that the Lias of Kent must be regarded as merely indicating a small extension of the sea beyond the limits of the Keuper lake. Moreover, this sea does not seem to have entered any part of Northern France except Normandy. The Lower Lias occurs in the Cotentin, and as far eastward as Bayeux, while thin beds representing the Middle and Upper Lias extend eastward to Caen and southward to May, where they rest on the Palæozoic rocks, the two together being less than 30 feet thick. Littoral representatives of the same divisions are found again in the Sarthe and Poitou, but there is no reason to suppose that any connection was established between the two Liassic seas.

It has been mentioned on p. 242 that Upper Lias was proved to exist below Rouen, and the Liassic sea must have reached that place either from the west or the south, for a boring at Havre

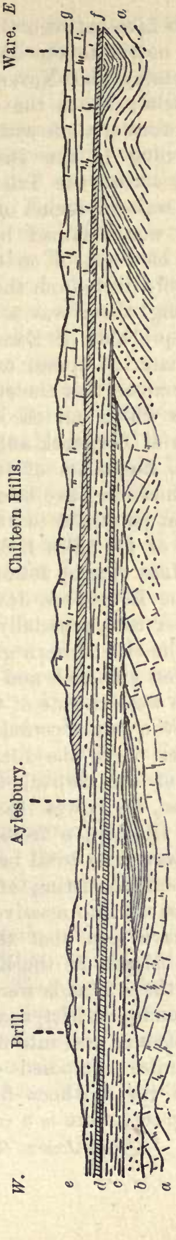


Fig. 41.—DIAGRAMMATIC SECTION FROM BRILL (BUCKS) TO WARE IN HERTS.

g. Chalk. *f.* Selbornian, etc. *e.* Upper Jurassic. *d.* Middle Jurassic. *c.* Lower Jurassic (Lias). *b.* Trias (Keuper). *a* Palæozoic rocks.

found no Lias between Great Oolite and Palæozoic rocks. Rouen is much nearer to the outcrop of May (70 miles) than to the Lias near Clamecy and Nevers (170 miles), on the south side of the Paris basin; hence the connection is more likely to have been with the former than with the latter.

Returning to the British area, the Lower Lias must have stretched across the Trias and Permian Beds in Devonshire far into the western region of Palæozoic rocks. An interesting bit of evidence was obtained by Mr. R. N. Worth in 1888 from the contents of a gravel on Cattedown near Plymouth:[1] the stones were chiefly flints from the Chalk and various rocks from Dartmoor, but among them was a large pebble of Lias limestone. This gravel is probably of Eocene age, or is a rearranged Eocene gravel, and its materials appear to have travelled from the north; we may infer, therefore, that the river which gathered them had its sources in valleys which cut through Chalk and Greensand into Lias, to the north of Tavistock and Launceston.

Again, fragments of stone identified by Mr. R. H. Worth as Liassic limestone have been dredged from the floor of the English Channel at points 30 to 34 miles S.E. of the Lizard, and one such fragment at 45 miles S.S.E. of that headland; hence it appears that the Lias outcrop follows that of the Trias down the Channel area. The Liassic sea doubtless extended somewhat farther than the Keuper lake, especially where rivers entered the latter; consequently the two western gulfs of the Keuper lake must have been more or less enlarged, and may even have approached one another round the western side of Cornwall, so as to convert Cornwall and South Devon into a peninsula.

Farther north the Liassic sea must have occupied the whole breadth of the Bristol Channel between North Somerset and Glamorgan, for Lower Lias is found in full force at Watchet and again in Glamorgan from Cardiff to Bridgend. Near the latter place, however, its basal beds have a littoral aspect, overlapping the Rhætic and consisting of hard, cherty conglomerate limestones, which pass up into massive shelly limestones.

We have seen that the Bristol and Mendip ridges formed a group of islands in the Keuper waters, and there is evidence that some of these islands were still unsubmerged by the Liassic sea. In the Mendip district, near Shepton Mallet, the ordinary clays and thin limestones pass into massive white limestones, associated with conglomerates composed of Carboniferous limestone and chert. Again, on the northern flank of the hills, near Chewton Mendip and Harptree, there is a compact cherty deposit containing Lower

[1] *Quart. Journ. Geol. Soc.* vol. xxxii. p. 236 (1876).

Lias fossils, and resting indifferently on Old Red Sandstone, Carboniferous Limestone, and Dolomitic Conglomerate.

Between Wells and Binegar the map of the Geological Survey shows patches of dolomitic conglomerate on the watershed ridge at about 800 feet, while the Liassic conglomerates do not now occur at so high a level. We must, however, suppose that they originally passed over the dolomitic conglomerate, and consequently over all the western parts of the Mendip Hills. Eastwards, however, the Inferior Oolite overlaps the Lias on to the Palæozoic rocks, and from this we may infer that during the Triassic and Jurassic periods the Mendip ridge rose to higher and higher levels toward the east, so that these were not submerged till after the end of Liassic time. We must remember that the whole of England has been tilted eastward at several subsequent epochs.

The Lias of the Midland Counties presents no features of special interest, and no other littoral deposits of this age have been found in England. The Lias is known to extend eastward beneath the newer rocks of Lincolnshire and Yorkshire as far as the Trias does, and we may safely assume that it underlies part of the North Sea in a broad band between the parallels of 53 and 55 N. Lat.

The occurrence of Lower Lias in the north-west of Ireland is important evidence of the extension of the Liassic sea over that area, but the shales are of normal character and are not littoral deposits, and do not therefore assist in defining the coast-line.

In the west of Scotland the lower part of the Lias resembles that of South Wales, consisting of hard limestones alternating with calcareous and conglomeratic sandstones. Above these are shelly limestones and shales. In Sutherland these beds are represented by estuarine deposits: at the base are the coarse sandstones and conglomerates mentioned on p. 248, with pebbles derived from the Trias, and these pass up into a series of sandstones and shales, with thin layers of clay and coal, the whole attaining a thickness of between 400 and 500 feet. Above these are marine beds representing the zones of *Am. oxynotus* and *Am. Jamesoni*, with a thickness of about 140 feet.

The only shore-beds of Middle Liassic age which have been preserved from destruction are those on the west coast of Scotland, described by Professor Judd in 1878.[1] They consist of calcareous sandstones 200 feet thick, and contain the fossils of the English Marlstone. In Mull they are represented by soft greenish sandstone with but few fossils. Similar sandy beds probably also existed in Sutherland, but the Lower Lias is there cut off by a fault, and no Middle Lias is seen.

[1] *Quart. Journ. Geol. Soc.* vol. xxxiv. p. 710.

It is rather remarkable that in several districts the shore-beds of the Lower Lias should be chiefly limestones, and we must infer that in these places, at least, very little detritus of any kind was carried down from the land at the beginning of the Liassic period. That this should be the case round the Mendip island is quite natural, but that limestones should be formed on the margin of the western inlet between Wales and Devon requires explanation; possibly this is to be found in the supposition that freshwater lakes existed in the country to the west, and that these for a time arrested and detained the mechanical detritus brought down by the rivers, leaving only the calcareous matter in solution to be carried on to the sea by the effluent stream. This, when added to the lime derived from the waste of the Carboniferous limestone along the shore, was more than the sea-water could hold in solution, and the formation of limestones was the result. In the Scotch case, we may suppose that the larger rivers flowed into the Sutherland basin, and that the shorter streams flowing into the western gulf conveyed at first only sand with carbonate of lime in solution.

Where older limestones are being actually eroded by the sea-waves a deposit of calcareous mud may be formed, and under certain conditions carbonate of lime in solution may be precipitated from sea-water, as seems to be the case off the coast of Marseilles at the present day.

B. *Physical Geography of Liassic Time*

The geography of the Rhætic and Liassic epochs was a simple and direct modification of that which prevailed during the preceding Triassic period. No local elevations and subsidences took place in the British area, for the Rhætic and Liassic Beds occupy the same basins of deposit as those which hold the Keuper marls; the great lakes or inland seas in which the latter were accumulated became by submergence the seas and bays in which the shales and limestones of the Lias were laid down.

This submergence set in doubtless toward the end of the Triassic period, and affected the whole of the Triassic north-European continent; the epoch of the Rhætic Beds marks the time when the depression had proceeded so far as to submerge the lowest tract of land which lay between the great salt lakes and the wide-spreading southern ocean.

The level of the water in the inland sea seems to have been somewhat below the level of the outer ocean, because the Rhætic Beds here and there passed beyond the limits of the Trias; but the difference of level cannot have been great, and the invasion of the area by the outer sea was doubtless accomplished quietly and with little disturbance of the previously formed deposits.

Let us consider the nearly parallel case of the Caspian Sea at the present day ; the level of this sea is 85 feet below that of the Black Sea, and it is surrounded by extensive low-lying areas which were formerly covered by its waters before the sea shrank to its present dimensions ; if, therefore, the waters of the Black Sea were admitted to the Caspian through the depression of the present barriers, they would quickly spread over a large area in Central Asia which is now for the most part a dry and sandy desert. It is unnecessary to suppose that anything like a cataclysmal influx of water would take place ; the first inroad would doubtless occur during the prevalence of a strong west wind, and if there were tides in the Black Sea, it would occur when there was a high spring-tide ; this would be only a temporary invasion, but as submergence went on the barrier would be broken through and a permanent connection established.

Two important results would follow from such a change : (1) Large numbers of the creatures living in the Caspian and of those coming in from the Black Sea would be killed from their inability to support the changed conditions of water and food ; and their remains would be laid out in layers on the bottom of the sea, thus forming *bone-beds.* (2) The climate and appearance of the surrounding country would be gradually altered ; evaporation from the newly-created sea would give rise to the formation of clouds ; these would fall again as rain on the neighbouring hills ; rills and rivers would come into existence, and the ordinary processes of detrition would be set in action ; the country would be irrigated and fertilised, and the products of erosion would be washed into the widening sea.

Such must have been the change which ensued after the Rhætic waters had filled the basins of the Triassic lakes. A scene of death and inactivity, of desert wastes and slowly shrinking lakes, was converted into a sea full of active creatures, bordered by a region where the plash of waters and the hum of insects were unceasing sounds.

The bone-beds testify to the suddenness of the invasion and to the destruction of many of the incoming fish and reptiles. It is clear also from the fauna of the succeeding shales and limestones that the mixture of sea and salt-lake water was for some time unfavourable to molluscan life ; the assemblage of species is a small one, and consists almost entirely of bivalves, their shells having that dwarfed appearance which is generally the case with those living in unfavourable habitats. No Cephalopoda, Gasteropoda, Brachiopoda, Echinoderms, or Corals occur, but all these come in with the Lower Lias, proving that further submergence opened up free communication with the outside sea, bringing in a greater depth of water and all the conditions favourable to the increase of molluscan life. The Liassic sea, indeed, with its large and active reptiles, its numerous fishes, and other inhabitants, must have presented a great contrast to the heavy and nearly lifeless waters of the salt Triassic lakes.

The plants and insects of the Rhætic and Lias also testify to the alteration of the climate, the humidity of the air, and the general fertility of the surrounding region. It is remarkable, however, that the insects are chiefly of a small size, and not such as might be expected to occur in association with the semi-tropical assemblage of marine creatures, but are rather such as would inhabit temperate climes at the present day. On this point Sir. A. Ramsay has some interesting remarks. During the Triassic and Liassic periods, he says, it is not improbable to suppose that the mountains of Wales were at least double their present height, and were, therefore, 5000 to 6000 feet high, so that if a tropical or warm temperate fauna existed along the coast, a cold temperate land-fauna might exist among the hills. Now Professor Edward Forbes, while dredging along the coast of Lycia (Asia Minor), observed "that during the rainy season the surface of the water was often partially covered with quantities of dead insects, washed into the sea from the neighbouring land. By far the greater number of these insects were not derived from the hot low-coast territories, but were borne to the sea from the more distant and lofty mountain lands (7000 to 10,000 feet high) by sudden floods which are then of frequent occurrence." They also, in accordance with the elevated regions from whence they came, bore the characters of temperate and cold climates; and Sir A. Ramsay thinks it probable "that the insect remains described by Mr. Brodie were washed from the mountain country we have described into the surrounding seas, and there entombed amid creatures of a tropical character." [1]

The geography of the British region, so far as concerned the relative positions of land and water, was similar to that of the Triassic period, and there is, therefore, no need to illustrate it by a separate map. The waters of the Liassic sea covered the whole area of the Triassic lake, and extended some little way beyond its margins. We have seen that the southern sea gained access to the British area through Central Europe and across the North Sea. It also covered large parts of Eastern and Southern France. This

[1] *Mem. Geol. Survey*, vol. i. pp. 324-5.

being so, we can understand how the Jurassic fauna and flora came to have their semi-tropical character. With continental land extending far to the east and west through the northern temperate zone, but not reaching far into the Arctic Circle,[1] and with an open sea spreading from tropical climes to its southern shores, we have exactly the conditions which would carry a high temperature and tropical productions far into the temperate zone.

As to the western limit of the British sea we have evidence of its shore-line in Glamorgan, and also in Monmouth east of Newport, where there is a small tract of Rhætic and Lias, resting on a small thickness of Keuper marl, which in turn reposes on the red marls of the Lower Old Red series. Another small patch occurs to the east of Chepstow at a very low level. The Lias at Newnham in Gloucestershire is close to the sea-level, but there and farther north we have to allow for the post-Liassic boundary-fault of the Trias; the throw of this is not great near Newnham, perhaps 100 feet, but it increases to several hundred feet along the border of the Malvern Hills, and consequently the basal-plane of the Lias rose to a much higher relative level in that direction.

The total thickness of the Lias between Newnham and Stroud is about 730 feet, and the distance from Newnham to the Carboniferous escarpment on the eastern side of the Forest of Dean is two miles. The Lias has a slight easterly dip, perhaps on the average of 1 degree, and if this is prolonged westward it would carry the base-line upward through about 180 feet. Adding 100 feet for the throw of the fault and we have the original shore-line of the Lower Lias cutting the flank of the escarpment at 280 feet above the present sea-level, and the top of the Lias rising to a height of 1010 feet. This is about the height of the escarpment at the present day, and as it must have been very much higher in Jurassic times, the sea of the Upper Lias is not likely to have passed over the Forest of Dean.

It would also be possible to calculate whether any of the Lias passed over the Malvern Hills, if we knew the exact amount of the displacement caused by the boundary fault which there brings Keuper marls against Archæan rocks. Permian breccia and the sandstones of the Upper Bunter must there underlie the Keuper series, but probably all the subdivisions are thinner by the Malvern Hills than they are below Tewkesbury, and the thicknesses may be estimated thus: Permian, 20 feet; Bunter sandstone, 250 feet; Keuper sandstone, 150 feet; and above these there may have been

[1] There are Jurassic deposits in East Greenland, Spitzbergen, Northern and Eastern Russia, and the fossils they contain make it improbable that there was any accumulation of ice round the North Pole at this time.

600 feet of Keuper marl, making a total of 1020 feet. Some Lias must also be allowed for, and we may put this at 100 feet, which gives a throw of 1120 feet as the displacement of the fault.

The present height of Midsummer Hill, near the southern end of the range, is only a little over 900 feet, but the Worcester Beacon (near Malvern) rises to nearly 1400 feet. Hence we may feel sure that the lowest part of the Lias did not overstep the Malvern Hills, but it is difficult to say whether the sea of the Upper Lias did or did not pass over them.

We may, therefore, assume that during the formation of the Lias the coast-line ran from the eastern border of Dean Forest to Malvern, the gaps which now intervene between the higher elevations being due to post-Jurassic erosion. Thence it probably trended north-westward through Shropshire and Denbighshire, and across the Irish Sea to the west coast of Ireland. As to the space now occupied by the Irish Channel no evidence is forthcoming, but if a gulf then existed on its site it probably opened northward and narrowed southward. From Ireland the sea extended over the site of the western Scottish lake, and thence probably up the Great Glen to the north-eastern basin; here the estuarine beds of the Lower Lias mark the debouchure of a large river, but the overlying marine beds show that as the submergence proceeded the sea gained on the land, while the sandy beds of the Middle Lias prove that the narrow water-spaces were soon silted up.

When discussing the extension of the Keuper marls across England we came to the conclusion that the whole of the southern and central parts of the Pennine chain were submerged beneath the great inland sea of later Triassic time. From this it follows that the Liassic sea also spread over this part of England, from Cheshire, Lancashire, and Westmoreland on the west to Yorkshire and Lincolnshire on the east, and thence across the whole breadth of the North Sea area. How far the subsidence of Liassic time may have carried the sea northward on to the land between Scotland and Norway we have no means of knowing.

In the south-west the Mendip Hills formed an island in the Liassic sea, parts of which seem to have remained above water throughout the whole of this epoch. Beyond Mendip the Liassic sea must have covered the greater part of Devon, the whole of Southern England, and a large part of the English Channel area as well.

2. The Middle Jurassic Series

A. *Stratigraphical Evidence*

Between the clays of the Upper Lias and the limestones of the overlying series thick beds of sand are frequently present, and were formerly regarded as being practically on the same horizon. More recently, however, zonal examination of the beds has shown that the Cotteswold sands are of earlier date than those of Dorset and Somerset, which are the equivalents of some of the Gloucestershire limestones; so that when referred to a certain horizon, that of *Ammonites striatulus,* the Yeovil and Midford sands lie above it and the Cotteswold sands below it. But all are below the zone of *Am. Murchisonæ,* and it is merely a question of where the stratigraphical plane between the Lower and Middle Jurassic series should be drawn.

If the *Striatulus* Beds are taken as the dividing line, the Inferior Oolite of Dorset consists mainly of sand, while in the Cotteswold area it is a variable series of calcareous grits, oolitic limestones, and marls. The overlying Great Oolite or Bathonian group is, on the whole, a more regular and continuous set of beds; and in the south-west part of England the whole series is entirely of marine origin.

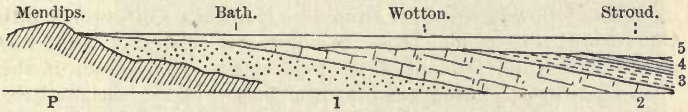


Fig. 42.—Section from the Mendip Hills to Stroud.

5. Upper Trigonia grit. 4. Oolite marl. 3. Pea grit. 2. Freestone. 1. Basal sands. P. Palæozoic rocks.

In the Mendip district the Midford sands and some of the overlying limestones seem to thin out against the ridge of Palæozoic rocks, but Dr. S. Buckman has shown that this is not an ordinary case of thinning out against a slope; the evidence collected by him points to the conclusion that the lower part of the Inferior Oolite may have passed over the Mendip ridge, but that after the accumulation of these beds there was a local uplift of the Mendip axis, accompanied by erosion and planation of the strata already deposited.[1] Thus the lower beds of this group dip off the Mendip ridge in the manner shown in Fig. 42, while the upper beds (5) pass across their truncated edges and over the eastern end of the Mendip Hills.

[1] *Quart. Journ. Geol. Soc.* vol. lvii. p. 149.

Fig. 43 illustrates the manner in which the Inferior Oolite rests directly on the Carboniferous Limestone in Vallis Vale near Frome. The photograph of this view was taken by Prof. S. H. Reynolds, who has kindly allowed me the use of it.

Minor flexures were also produced in the Cotteswold district, and the summits of the anticlines were similarly planed off before the deposition of the beds known as the "Upper Trigonia Grit." Moreover, the surface of planation so formed was perforated by lithophagous Mollusca before the upper calcareous grits were spread over it, so that the uprising portions of the sea-bed must have been exposed to the action of currents and perhaps of waves in a very shallow sea before subsidence again ensued and deposition began afresh.

This shallow sea swarmed with all kinds of marine creatures, and compound corals are so abundant in some of the beds as to suggest the neighbourhood of coral-reefs, though no actual banks or walls of coral-rock have yet been discovered.

The main axis of uplift was along the Mendip and Pewsey line, but another strong anticline traverses the Vale of Moreton from north to south, and along the central axis of this line the upper part of the Inferior Oolite rests directly on the clays of the Upper Lias. All these lines of flexure seem to converge on a point near Pewsey in Wilts.

When followed eastward from the Northern Cotteswolds into Oxfordshire, the whole series becomes much thinner, and this attenuation is independent of the local cutting out of beds in the Vale of Moreton, for on reaching the valley of the Cherwell the Inferior Oolite is represented by 20 to 30 feet of brown sand, calcareous sandstone, and flaggy limestone, while the overlying Bathonian is not more than 100 feet thick. There is at the same time evidence of the vicinity of land in this direction, not only from the sandy character of the Inferior Oolite, but from a thin zone of estuarine beds at the base of the Great Oolite. These are known as the Stonesfield Beds, and contain the remains of many plants and terrestrial animals.

In the continuation of the series to the north-east these estuarine beds thicken at the expense of the Great Oolite limestones, while other beds of a similar character replace part of the Inferior Oolite. Moreover, in Northampton, the two estuarine groups are separated by a plane of erosion or unconformity, and the whole series is in some places reduced to less than 100 feet, of which only 30 feet are marine limestones.

Even these changes do not exhaust all the facts which have to be taken into consideration. Throughout the counties of

Photo *S. H. Reynolds.*

Fig. 43.—VIEW OF A QUARRY IN VALLIS VALE, NEAR FROME, SHOWING THE RAGSTONE BEDS OF THE INFERIOR OOLITE OVERLYING CARBONIFEROUS LIMESTONE.

Northampton, Rutland, and Lincoln the lowest beds are ferruginous sands and ironstones, which rest on an eroded surface of the Upper Lias shales, and generally have a Pebble Bed at the base, composed of rolled fragments of limestone, phosphatic nodules, and Ammonites, all derived from the Upper Lias. These ferruginous beds contain marine fossils, but pass up into estuarine beds, and it is evident that the quiet conditions under which the Liassic shales had been deposited were disturbed by a change which introduced a strong sand-bearing current. Such a change would be produced by an upward movement, which was sufficient to shallow the sea and alter the tidal currents, without producing actual emergence of these particular tracts.

In Lincolnshire there is a greater thickness of marine limestones, a lenticular mass of limestone coming in between the two estuarine groups, but this becomes thin again in the north of that county, and in Yorkshire the estuarine beds thicken, so that they eventually form a thick series of deposits in which marine limestones are quite subordinate features. As this Yorkshire series is such a contrast to that of the south-western counties, a brief account of its component members may be given.

At the base of the section are marine sandstones and ironstones (about 50 feet thick). Above these is a group of estuarine sandstones and shales, with much carbonaceous matter and thin seams of impure coal; this group is 280 feet thick near Whitby, but thinner to the southward. Then comes a band of calcareous sandstone, which contains marine fossils, and appears to be the attenuated representative of the Lincolnshire limestone; but above this is another mass of estuarine deposits, from 50 to 100 feet thick, containing several workable seams of coal. This group is succeeded by the Scarborough limestone, a lenticular mass, which is thin on the coast, but thickens to the west and north-west. Above this limestone is a third set of estuarine shales and sandstones, from 120 to 220 feet thick, which are generally supposed to represent the Great Oolite, as they are covered by the Cornbrash, with its usual marine fossils. Thus, out of a total thickness of about 650 feet, no less than 550 are estuarine beds—a fact which proves the Yorkshire basin to have been in close proximity to land of a continental character, and to have received the deposits of a large river, the mouth of which lay apparently to the north or north-west of Yorkshire.

In the eastern counties the whole Middle Jurassic series, like the Lias, passes eastward beneath the newer rocks and thins out against the shore-line of the buried eastern land. Borings at Culford in Suffolk and at Ware in Herts have proved that these beds did not extend so far east as those places, but farther south other borings have proved their presence, and have shown that in the south-east of England they overlap the Lias and rest directly on the Palæozoic platform. Moreover, the Inferior Oolite (Bajocian) thins out and disappears before the Bathonian Beds, which overlap all the older Jurassic deposits.

Thus a boring at Richmond, after piercing the Cretaceous strata, found sandy clays and limestones with Great Oolite fossils, and 87 feet thick, resting directly on red (Devonian ?) rocks. At Meux's Brewery in London similar beds occurred in the same position, the rocks below being undoubtedly Devonian.

Recent borings in Kent have shown that the Middle Oolites follow the Lias, overlap it, and then themselves become thinner eastward, just as might have been expected. At Brabourne, near Ashford, they are 189 feet thick, part of this probably being Bajocian. At Swingfield, farther east, there is 154 feet, of which about 54 is Bajocian ; and at Barham the thicknesses are nearly the same. At Dover there is some doubt about the thickness of these beds, but if those from 992 to 1135 feet are so classed, their thickness is 143 feet, and they include a bed of lignite in the upper part, while the base is a sandstone 15 feet thick.

At Nonington, north-east of Dover, according to Mr. Burr, there is 91½ feet of Bathonian, to which a few feet of Cornbrash must be added, making a total of, say, 104, which rests on a few feet of Lias ; but the age of the beds has not yet been accurately determined. It is clear, however, that the Bathonian extends beneath all the southern part of Kent, and must be prolonged eastward some way beneath the southern part of the North Sea.

In the Boulonnais, near Desvres and Blacquerecque, there is a series of sands and sandy clays with layers of lignite, varying in thickness from 60 to 150 feet, and lying directly on Palæozoic rocks. Northwards, however, they thin out, and are overlain and overlapped by limestones of Great Oolite age, which also eventually thin out both to the north and east. The lower beds may be partly of Bajocian age, and are evidently estuarine deposits formed near the mouth of a river.

The Middle Jurassic Beds crop out again in Normandy, where both the Bajocian and Bathonian are well developed. Southward they overlap the Lias near May, and though the Bajocian thins considerably, the Bathonian extends through Orne and Sarthe into Central France. How far those beds pass eastward under the Paris basin is not known, but it would appear that the Bajocian at any rate is not continuous in that direction, for it is stated that a boring at Havre found the Bathonian resting on the Palæozoic rocks.

Returning to British soil, and taking note of the fact that no beds of this age have escaped destruction round the borders of the Irish Sea, it is interesting and instructive to find them represented by thick deposits at certain points on the western side of Scotland. No one can doubt that they succeeded the Lias of Antrim, but not a vestige of them has been found in Ireland, and the Scottish relics are consequently now separated by a distance of 340 miles from the deposits in Worcester and Gloucester, with which they were once connected.

In Skye and Raasay the Inferior Oolite is represented by shales, sandstones, and limestones of marine origin, 380 feet thick, but including 60 feet of white sandstone, with bands of shale containing plant remains. Of the Great Oolite there is no marine representative, its place being taken by a remarkable formation which is evidently part of the delta of a large river ; the mass of this consists of grey and white sandstones often current-bedded and ripple-marked, but above and below these are groups of black shale and limestones, in which freshwater shells are abundant, together with the remains of reptiles, turtles, and fish. Professor Judd remarks upon the striking resemblance which these beds present to the Purbeck series of Dorset. Similar beds occur on the east coast of Sutherland, where the highest member of the series is a coal-seam $3\frac{1}{2}$ feet thick, resting on black shales with plants and crushed freshwater shells.

B. *Physical Geography*

Where the succession of purely marine beds is most complete, as in Dorset and parts of Gloucester, there is a passage from the Liassic series into the Bajocian, but it is generally a rapid one, and there is at the same time a great change in the fauna ; very few of the Upper Lias species ranging up into the zone of *Ammonites jurensis*, which is therefore the most convenient base-line for the mid-Jurassic series.

The facts imply that a considerable and rapid change took place in the physical conditions of the region, and the superposition of calcareous sand and limestones on clays and shales might lead us to suppose that the change was produced by subsidence and a deepening of the sea ; but as stated on p. 10, limestones may be formed in any depth of water, and oolitic limestones in particular are generally of shallow-water origin. The change, therefore, may be due to upheaval, and we have seen that there is definite evidence of local uplifts during the formation of the Inferior Oolites.

Moreover, the limestones are not continuous; between Oxford and Northampton the Inferior Oolite is replaced by shallow-water beds which are in the upper part of estuarine origin, while the estuarine beds of the Great Oolite extend over a wider area, and the contents of the Stonesfield slate bear testimony to the vicinity of land. It would appear that the water became so shallow across this part of England that for a time it was a tract of low flat land covered with lagoons of brackish water.

There are, in fact, five salient facts which have to be explained: (1) The more or less sudden change everywhere in the character of the sediment; (2) the evidence of erosion at the base of the series in the Midlands; (3) the local breaks which occur in the Inferior Oolite; (4) the estuarine deposits found in the Midland Counties, in Yorkshire, and on both sides of Scotland; (5) the overlap of the Great Oolite (Bathonian) in Southern England and in France.

In the first edition of this book I suggested that the cause of these changes and evidences of erosion was a slight but general elevation of the whole region, whereby the velocity of the rivers was increased, and they were made to deepen their channels so as to cut into the older rocks which underlay the Coal-measures; the result being that they carried less mud and more sand, and at the same time would convey more calcareous matter in solution. So far as the initial change is concerned, this is probably a correct explanation, but subsequently I pointed out that while there seems to have been elevation of the northern and north-western districts there was also subsidence of the southern areas, and consequently that the movement may have been a tilt from north to south, like that which has affected Norway and Sweden in recent times.

Both these suppositions were, however, too generalised, and did not sufficiently take account of the succession of events and of the successive horizons in the series at which evidence of physical change occurs. The history of the time evidently includes more than one movement of the crust and more than one change in the physical geography of the region.

The conditions under which the earliest beds of the series were deposited certainly seem to indicate a general uplift of nearly the whole region, causing a shallowing of the water, a change in the supply of sediment, and alterations in the tidal currents. In the southern area the uplift only resulted in the transport of sand instead of mud, but in the Midland Counties the uplift may have been greater, for its effects are certainly more apparent. In that area the sea became so shallow that its floor was scoured by tidal currents, eroding the surface of the Lias, and for a time preventing the deposition of any kind of sediment.

The next episode was more local and spasmodic, producing small uplifts or bulgings of the sea-floor in the south and west of England, the evidence of which is found in the discordances between the upper and lower parts of the Inferior Oolite in Somerset and Gloucestershire. It is not likely, however, that these discordances are confined to those districts ; if we could strip off the covering of newer deposits we should probably find similar breaks throughout the southern counties. In fact, looking at the directions of the two strongest inter-Bajocian flexures, it seems probable that the chief movements were along the old Armorican lines in the South, and along a continuation of the Pennine range in the Central Counties.

In the north-eastern part of the British region, judging from the succession in Yorkshire where the Bajocian group is so thick and so largely represented by estuarine deposits, there was evidently a great contraction of the sea-space, with the resultant formation of a large swampy and estuarine area, into which one or more large rivers poured sediment derived from a northern land. The characters of the Yorkshire deposits recall those of the Coal-measures, and after the first elevation of the region, it seems to have been subject to oscillations of level, or else there were episodes of stationary conditions alternating with slight subsidences, which occasioned invasions of the southern sea. It is also evident that the position of the deeper channels and bays was frequently changed, so that they were sometimes in the western and sometimes in the eastern part of the area.

During the deposition of the beds known as the "Dogger," Mr. Strangways thinks the deeper water lay on the western side of Yorkshire, while the eastern part was shallow water, more or less, between tide-marks.[1] The succeeding estuarine beds thicken to the north, whence we infer that the material came from that direction ; and the greater part of the area seems to have been silted up to form a swampy alluvial plain, on which grew a dense vegetation, consisting largely of Equisetaceæ, Cycads, and Ferns.

"This vegetation," writes Mr. Strangways, "produced the thin coal-seams that are dispersed throughout the Lower and Middle estuarine series, and which vary in thickness from about 3 feet to mere streaks of coaly matter. That these coal-seams are composed of plants which actually grew upon the surfaces where we now find them, and are not the result of drifted vegetation, as has been

[1] "Jurassic Rocks of Britain," Yorkshire, *Mem. Geol. Surv.*, 1892, p. 390.

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suggested, is proved by an underclay representing the old soil being found beneath them full of their decayed roots."

This stationary period was followed by subsidence, by means of which the sea was enabled to advance northward as far as a line drawn between Northallerton and Whitby, and over this area the water became clear enough to support the existence of Polyzoa, Terebratulæ, Echinoderms, and even a few Corals. After a time, however, the sea was forced to retreat, and the swampy plain was re-established, continuing to exist till another sinking of the ground brought the sea once more over the south-eastern part of the area and led to the formation of the Scarborough limestone, with *Ammonites humphriesianus* and other marine Mollusca.

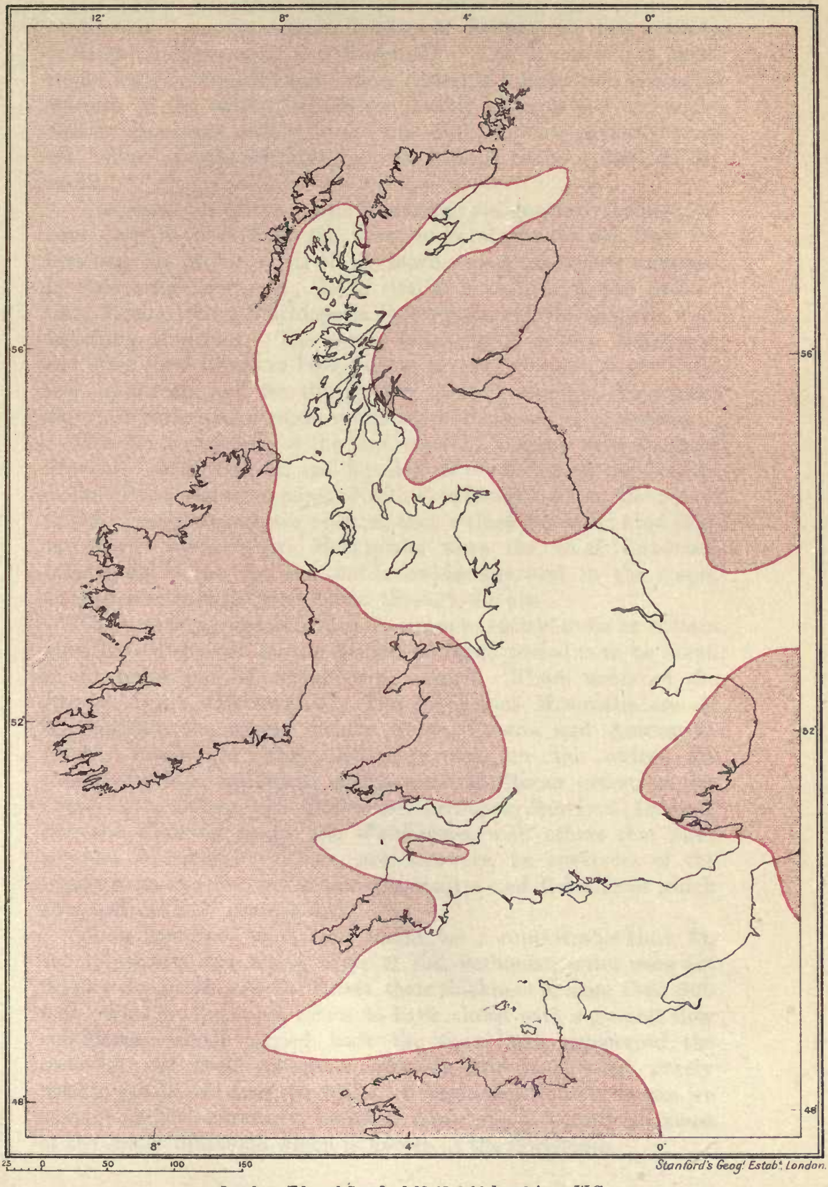
The general inference is that throughout this time the extent of the Scoto-Scandinavian land was increased by the addition of a broad tract of lowland along its southern side ; a lowland never raised far above the sea-level of the period, and indented by the estuaries of several large rivers which drained a considerable area of the northern land.

With the inception of Bathonian time all the local movements above recorded seem to have ceased, and were succeeded by a general tilt of the whole region, by which the northern part was raised and the southern part was depressed ; while, of course, there would be an intermediate area wherein there was little or no movement in either direction. On this theory three separate sets of facts find a natural explanation. The estuarine representatives of the Bathonian in Scotland, and the similar beds in Yorkshire, were formed within the area of elevation. Lincoln, Rutland, and Northampton, where the small thickness and regularity of the beds indicate a slow rate of accumulation, were part of the stationary belt. Lastly, in the southern area we have the extension of the Bathonian beyond the lower beds, which is the usual result of subsidence.

In Fig. 44 I have endeavoured to restore the probable limits of the Bathonian sea in accordance with the views above expressed. It will be noticed that I have brought the northern land well down to the east of Yorkshire, and have left but a narrow opening eastward between it and the land which still occupied East Anglia and the southern part of the North Sea area. On the other hand, the southern part of this Anglian land was still further submerged, and its shore-line consequently lay farther north and east than it had been in Liassic or Bajocian time.

Although there is no actual proof that the Bajocian and Bathonian Beds extend broadly under the Paris basin, yet it seems to be the belief of French geologists that they are, or were, really

Fig. 44.—GEOGRAPHY OF GREAT OOLITE TIME.



London: Edward Stanford, 12, 13, & 14, Long Acre, W.C.

continuous from the eastern borders of Brittany to their existing outcrops in Champagne and Burgundy. The fauna of the limestones both in England and France certainly testifies to a perennial warmth of the waters, which can hardly be explained unless the British sea opened widely toward the south, and was protected from the inflow of cold currents by a continuous tract of land on the north.

The materials of the oolitic limestones are generally believed to have been derived from the waste of coral-growths and from the breaking up of the shells of the marine creatures which swarmed in their neighbourhood. As in similar situations at the present time, Echinoderms, Brachiopoda, Pelecypoda, and Gasteropoda were especially abundant. The corals which occur in the limestones, and often form layers or beds, belong to genera which might build true coral-reefs, and for the growth of such corals at the present day clear water and a warm temperature are essential conditions.

The fauna and flora of the land were in keeping with those of the sea. Ferns, Cycads, and Equisetums abounded on the borders of the rivers, and were mingled with Coniferous trees on the higher slopes ; huge Dinosaurian reptiles, that walked on their hind legs, and small insectivorous Marsupials, were the chief vertebrate inhabitants of the dry land, but crocodiles swarmed in the rivers, and bat-like Pterodactyles flitted through the air.

The nearest approach in modern times to such a scene as Britain must have displayed in the Middle Jurassic period is to be found in Australia and its neighbouring islands. There many of the Jurassic types still survive. The indigenous Mammalia are all Marsupials ; the plants include Ferns, Cycads, and Araucarian pines. Coral-reefs fringe the shore, and in the waters are Cestraciont fish, and many of the same Molluscan genera as are found in the Oolites, viz. *Delphinula*, *Neritopsis*, *Solarium* (*Torinia*), *Stomatia*, *Trigonia*, *Corbis*, and *Waldheimia*, with others that have a wider distribution. There, are, however, no survivors of the huge marine reptiles, or of the Ammonites and Belemnites which swarmed in those Jurassic seas.

These conditions must have lasted for a considerable time, for the limestones and marly clays of the Bathonian series were not rapidly deposited, and in Dorset their thickness is more than 600 feet. Finally, the epoch seems to have closed with a general slow subsidence, which carried back the shore-lines, submerged the estuaries and their marginal lowlands, and established purely marine conditions over the whole of England ; for only so can we account for the continuity, constant characters, and small thickness of the shelly limestone which is known as the Cornbrash.

3. Upper Jurassic Time

A. *Stratigraphical Evidence*

Like the Lias the Upper Jurassic series is essentially argillaceous, but it includes large lenticular and episodal developments of limestone and calcareous sand. The succession is most complete in the south of England, where it consists of the following members in descending order:—

5. Purbeck Beds, estuarine and fresh water.
4. Portland limestone and sands.
3. Kimeridge Clay.
2. Corallian limestone and sands.
1. Oxford Clay.

The Oxford Clay is generally more or less sandy at its base, but the mass of the formation consists of dark grey or blue clay, with layers of calcareous nodules. In the south of England it is from 300 to 600 feet thick, and it maintains the same character and average thickness to the north of Lincolnshire, but then becomes thinner, and in Yorkshire it is only from 100 to 150 feet thick, the lower part (30 to 80 feet) consisting of sandstones and sandy limestones (Kellaways Rock).

In Yorkshire the clays thin to the north-west, and the sandstones thicken in that direction. Commenting on this fact, Mr. Hudleston remarks that if the traveller notes how in the Hambleton Hills a mere strip of clay is intercalated between 100 feet of Callovian sandstone below and 100 feet of Calcareous Grit above, he may easily imagine them continued to a point where the upper and lower sandstones should coalesce, and no clay be left to represent the great argillaceous deposit which extends in unbroken continuity from Dorset to Yorkshire. A little further stretch of the imagination will restore a massive deposit of sandstone resting against the shore of the Old Oxfordian sea above the flanks of the Palæozoic hills which may be seen to bound the western horizon.[1]

Though in the passage which I have abridged Mr. Hudleston directed his traveller's gaze *westward*, and seems to have thought that there may have been land over the Pennine ranges, he knew that most of the Callovian sand must have come from the north, for on p. 372 he regarded the deposit as "a sandbank, more or less connected with the shore, the land supplying the material lying somewhere to the north and west." As a matter of fact, it prob-

[1] *Proc. Geol. Assoc.* vol. iv. p. 370 (1876).

ably came entirely from the north and N.W., for I strongly suspect that the Oxfordian sea spread completely over the greater part of the Pennine area, as the Liassic sea had done.

It is true that some of the Pennine ridge may have been raised again above sea-level in Bathonian time, but the fauna of the Callovian indicates a decided increase in the depth of the water. Thus in the Forest Marble and Cornbrash only three species of Ammonites are known, while in the Callovian of Yorkshire no fewer than forty-one species of Ammonites occur, only one ranging up from the Cornbrash and twenty passing up into the Oxford Clay. Mr. Hudleston himself remarks that "Probably this great sandbank was deposited during a submergence of this region far more continuous in time and extended in space than those more partial depressions which during the period of the Lower Oolites (Middle Jurassic) had in this region intercalated the spoils of the sea with those of the estuary and the marsh. This more continuous descent seems at length to have removed or lowered barriers which had hitherto kept out the waters of a sea swarming with strange Cephalopoda."

One of these barriers was undoubtedly that tract of land which occupied the southern part of the North Sea, and stretched from Belgium into the eastern part of the British area throughout the Liassic and Middle Jurassic periods. The borders of this ridge began to be submerged during the formation of the Great Oolite, and there can be little doubt that the subsidence continued during the succeeding epoch.

Borings in the south-east of England have shown that the Oxford Clay underlies the whole of Sussex and Kent, from Battle on the south to Chatham on the north, and eastward beneath Ashford and Dover to beyond the eastern limits of Kent. At Chatham, however, it seems to be little more than 40 feet thick, this small thickness, as well as its complete absence under London, being unquestionably due to the erosion and planation of the Upper Jurassic Clays, which was effected partly by the upheaval of the eastern area into dry land at the close of the Jurassic period, and partly by its subsequent subsidence during Cretaceous time. By these erosions such Upper Jurassic Beds as had spread over the eastern counties north of the Thames were completely removed before the deposition of the Gault.

The probable relations of these beds to the Cretaceous strata of Kent are shown in Fig. 45, and evidence that the Oxford Clay was undergoing erosion during the earlier part of Cretaceous time is furnished by the occurrence of worn Oxfordian fossils in the Vectian (Lower Greensand) of Godalming (Surrey).

The beds known as Coral Rag and Calcareous Grit are a variable set of oolitic and coralline limestones and calcareous sandstones, which are only developed as such rocks in the southern counties and in Yorkshire, being represented by clays with thin layers of limestone in the counties of Bucks, Beds, Hunts, Cambridge, and Lincoln. At Upware near Ely, however, there are the remains of a small isolated coral-reef, part of the mass consisting of coral-rock, and part of a whitish calcareous marl, which is evidently a consolidated calcareous ooze, such as is found in deep water outside many coral-reefs at the present day. The marl contains no corals, though it may be largely made up of their disintegrated fragments, the only fossils being Echinoderms and a few bivalve Mollusca.

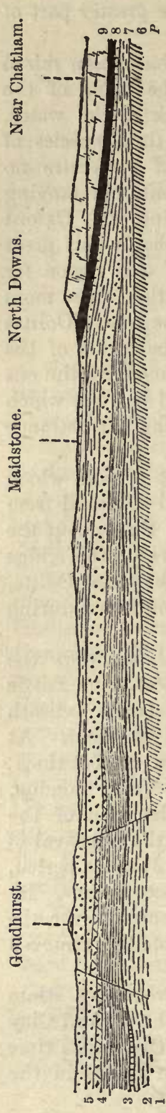


Fig. 45.—SECTION ACROSS PART OF KENT. Distance about 25 miles.
(Details of northern part after W. Whitaker.)

9. Chalk (Lower, Middle, and Upper).
8. Selbornian (Gault and Upper Greensand).
7. Vectian (or Lower Greensand).
6. Weald Clay.
5. Hastings Sands.
4. Purbeck Beds.
3. Portlandian and Kimeridgian.
2. Corallian.
1. Oxfordian.
P. Palæozoic rocks.

At present the only indication of a shore-line to the Oxfordian and Corallian sea which has been discovered is in the north-east of Scotland, where the Oxford Clay, over 300 feet thick, and containing the usual fossils, is succeeded by a zone of white cherty sandstone, with the fossils of the Lower Calcareous Grit, overlain by a mass of estuarine sandstones with layers of lignite; these are 400 feet thick, and are surmounted by marine beds with Coral Rag fossils.

That both groups were also deposited over the tracts previously covered by the Lias and Oolites in Ireland and the West of Scotland is highly probable; small remnants of Oxfordian still exist in the islands of Skye and Eigg, and its absence in Ireland and in the north-west of England is to be attributed entirely to denudation. From the position of the Upper Cretaceous rocks in Scotland we know that the Jurassic rocks of that country were largely eroded and destroyed during the interval between these two systems. Probably the whole of Scotland and Northern England became a land surface in Purbeck, Wealden, and Vectian times, and before the Scottish Greensand was formed erosion had cut down through all the Oolites, and in many places through the Lias and Trias also. We are, therefore, quite justified in concluding that before this erosion took place the Oxfordian of Skye was covered by representatives of the Corallian and Kimeridge Clay, and that the whole mass was continuous with that which still remains in England.

The Kimeridge Clay consists of dark clays and carbonaceous shales, which are continuous across England. They are thickest in the southern counties, being about 1000 feet in Dorset, and still more in the sub-Wealden boring (Sussex). Toward the Midland Counties they become thinner, being apparently not more than 100 feet at Headington, near Oxford. Northward, however, they thicken again, till in Lincolnshire the group is at least 600 feet thick, and it may be as thick at Speeton in Yorkshire.

It is, indeed, a notable fact that all the three stages above mentioned become thinner in the Midland Counties, as can be seen from the following table of comparative thicknesses :—

	S. Wilts.	Bucks.	Lincs.	Yorks.
Kimeridge Clay . .	600	120	600	(?) 500
Corallian . . .	150	60	20	300
Oxfordian . . .	550	450	300	140
	1300	630	920	940

From these facts we may conclude that the subsidence of Upper Jurassic time was greatest in the southern area, for near Weymouth the beds are still thicker than in Wiltshire, having a combined thickness of 1700 feet. There seems also to have been a considerable subsidence in the north, both in Yorkshire and in Scotland ; while in the Midland Counties the much less thickness of deposit suggests that the movement was of less extent.

In Scotland the Kimeridge Clay is represented by a thick and variable series of beds, chiefly estuarine sandstones in the lower part, with marine grits, shales, and limestones (500 feet thick) in the upper part, the highest beds being ferruginous sandstones.

Near the Ord of Caithness thick beds of breccia occur amongst the marine shales of the Kimeridge Clay, and their formation is explained by Professor Judd as follows : "The alternation of the brecciated beds with the finely laminated and quietly deposited strata and the confused arrangement of the blocks in the former, their admixture with trunks of trees, stems of cycads, and other plant remains, seem to indicate that the quiet deposition of the semi-estuarine beds was interrupted by the occasional occurrence, in the rivers just alluded to, of floods of the most violent character. These appear to have swept angular masses, just separated from their parent rock by frosts or landslips, subangular masses which had lain for a time in the course of the streams, and the rounded pebbles of the river-beds, along with trunks of trees torn from their banks, all in wild confusion out to sea, where they were mingled with the sea-derived materials of the shell-banks and shoals." [1]

The highest ferruginous sandstones resemble the Northampton Sands; they indicate very shallow water and are probably of estuarine origin, but they have not yielded any fossils. The series ends abruptly with these beds.

With regard to the eastern extension of the Kimeridge Clay in England, it is probable that it followed the Oxfordian and Corallian, spreading with them across the greater part of the North Sea area, and probably over some of the Franco-Belgian land as well. That it originally covered our eastern counties north of the Thames may be inferred from the manner in which it occurs beneath the south-eastern counties. The following are particulars of the several subdivisions of the Upper Jurassic series traversed by some of the recent borings in Kent. Unfortunately no dependence can be placed on the published accounts of the Jurassic Beds traversed by these borings, but Mr. Lamplugh has had the opportunity of examining the cores from some of these borings, and a joint Memoir by him and Dr. Kitchin is now in course of preparation. With its publication much more accurate details of four of the borings will be available ; in the meantime I am indebted to them and to the Director of the Geological Survey for permission to use their corrected readings of the borings at Penshurst, Pluckley, and Brabourne, so far as the Upper Jurassic Beds are concerned. The localities are taken in order from west to east, in order to show the attenuation of some and disappearance of the higher beds as they pass in an easterly direction.

[1] See *Quart. Journ. Geol. Soc.* vol. xxix. p. 195.

	Penshurst.	Pluckley.	Brabourne.	Elham.	Ellinge.	Barham.	Fredville.
Purbeck Beds	494 (?)	103	56	(?)			
Portlandian .	131	70	31	17½	0	0	0
Kimeridgian .	622	526	262	108 no base	186	0	0
Corallian .	not reached	not reached	307		164	156	54
Oxfordian .			210		198	164 (?)	161

It will be seen that the thickness of the Kimeridge Clay has diminished very considerably between Pluckley and Brabourne, and again between Brabourne and Ellinge, before coming under the plane of Cretaceous erosion. It is also seen that this plane of erosion will account for the entire absence of Kimeridgian at Barham and Fredville ; moreover, in a boring at Hougham, near Dover, there is still a remnant of Kimeridge Clay in the shape of 34 feet of shale and limestone. We may, therefore, safely assume that the Kimeridge Clay originally extended to and beyond the eastern limits of Kent.

The same may be said of its extension northward into and over the area north of the Thames. The Penshurst boring was not carried to the base of the Kimeridge Clay, which is probably much more than 622 feet at that place. North of Penshurst and Pluckley no boring has yet reached it except one at Rochester, where its presence seems to be indicated by fossils in hard clay between 813 and 850 feet, with Corallian below ; but at Chatham Dockyard clay supposed to be Oxfordian was entered at a depth of 943 feet, and the difference of level suggests that the higher beds may have been cut out by valley erosion in Cretaceous time.

Southwards all the Upper Jurassic strata extend into France, and some of them are exposed in the cliffs of the Boulonnais. There the Kimeridgian consists of sandy clays, shales, and limestones ; the Portlandian of sands and limestones with marine fossils overlain by estuarine beds containing *Corbula*, *Cyrena*, and *Cerithium*. There is a complete passage from one group to the other, and their combined thickness is not more than 500 feet, the portion referred to the Kimeridge being only half that amount, so that it has thinned out very considerably in passing south-eastward across the Channel.

These beds, with the Corallian and Oxfordian below, extend eastward from Boulogne to Desvres, and doubtless spread under the whole of the Paris basin, since they crop out all round it. North-eastward, however, toward Hardinghen and Caffiers, they become thinner, and at the same time are cut off by the basal-plane of the Cretaceous series, just as in Kent.

Returning now to England, we have to consider the facts presented by the Portland and Purbeck Beds, the lithological characters of which indicate the commencement of great physical changes, and exhibit a marked contrast to the great argillaceous formations below them.

The Portland Beds form an interesting episode in the upper part of the Jurassic system, their special and typical facies being confined to the southern part of England and the Boulonnais. They attain their greatest thickness at St. Alban's Head in Dorset, where they are over 300 feet, while at Portland they are only 180 feet. They consist of sands and marls in the lower part, and of limestones in the upper. The chalky limestone found both at Upway and in the Vale of Wardour has the aspect of a deep-water rock, but Mr. W. Hill examined a slice of it under the microscope, and found that it is quite different from chalk. It consists entirely of minute particles of calcite, probably derived from the destruction of shells, but without any recognisable portions of shell, except of some small Ostracod Crustacea. As it is preceded and followed by beds of distinctly shallow-water origin, fine sandstones, and current-bedded Oolites, the water can never have been very deep, but during the formation of the chalky beds it must have been exceptionally clear, and free from the invasion of mud-bearing currents.

At Swindon, in North Wilts, there are again good exposures of Portlandian Beds, which are about 100 feet thick, and are overlain unconformably by Purbeck Beds, so that they may originally have been thicker. The highest bed is a marly or chalky limestone, from 1 to 6 feet thick, and there may have been not only more of it, but also some other sandy and oolitic limestones, like those which overlie the chalky beds in the Vale of Wardour.

North of the Thames, from Crendon to Aylesbury, the lower part of the Portlandian consists of sandy clay and sand (30 to 40 feet), while the higher part has a Pebble Bed at its base and is a variable series of thin limestones, sands, and marls (20 to 30 feet). The beds are clearly thinning out, and their outcrop does not extend beyond Dunton and Wing, near Leighton Buzzard, being there overstepped by the Gault. They are, in fact, cut off by the basal-plane of the unconformable Cretaceous Beds.

That the Portland Beds and Kimeridge Clay were both undergoing erosion in Lower Cretaceous time is shown by the occurrence of fossils derived from both stages in the Vectian sands of Bedfordshire, the fossils occurring as rolled phosphatised nodules.

The same is the case in Lincolnshire, where a nodule bed containing derived Portlandian fossils is found at the base of the Spilsby sandstone. In Yorkshire also there is a nodule bed at the base of the Speeton Clay, containing Ammonites which are referred by Professor Pavlow to Russian species of Portlandian age (*Perisphinctes scythicus* and *P. Panderi*).

The beds represented by derived fossils were probably of the age of the Portland sands, and there is no proof that any equivalent of the Upper Portland Beds was ever formed in the northern area. The beds above this gap in the succession contain species of Ammonites and Belemnites which are characteristic of higher zones in the Russian series and are considered by Professor Pavlow to be the marine equivalents of the Purbeck group, but they pass up both in Yorkshire and Lincolnshire into beds which are certainly of Cretaceous age. It would seem, therefore, that though this area partook in the general uplift, it sank below sea-level rather before the time of the transition from Purbeck to Wealden in the south of England.

The Purbeck Beds exist only in the south of England ; they consist of limestones, shales, marls, and black earths in thin layers, which exhibit alternations of terrestrial, freshwater, and marine conditions. Near Swanage in Dorset they are 400 feet thick, but they thin rapidly both to the west and north.

In the Lower Purbeck group of Dorset dirt-beds or carbonaceous soils are a conspicuous feature, and the presence of rooted stumps of cycadean and coniferous trees proves them to be actually terrestrial surfaces. At the base of the Middle Purbeck is a carbonaceous shale from which twenty-four species of small marsupial mammals, together with the bones of several crocodiles and lizards, have been obtained. It has been pointed out by Professor E. Forbes and Mr. C. J. A. Meyer, that the changes from freshwater to marine deposits are abrupt, and that there is no real intermingling of marine and freshwater fossils in the same stratum, but a gradual return from brackish to freshwater conditions ; that these facts seem to indicate lacustrine areas which were subject to occasional and sudden inroads of the sea, and were therefore, in all probability, lakes or lagoons situated in a silted-up bay or gulf.

In Dorset these lagunic conditions are most conspicuous in the upper part of the Lower division, beds which contain a stunted marine and brackish-water fauna, and include layers and nodules of gypsum, and sometimes exhibit cavities which have been occupied by cubic crystals of sodium chloride. From these facts it is clear that the lagoons were sometimes barred off from the sea and their waters so evaporated and condensed that some of the salts were crystallised out from time to time.

The Middle Purbecks contain some purely marine beds; but the Upper division consists almost entirely of freshwater deposits, and the limestones are mainly composed of *Paludina* shells, forming the well-known Purbeck Marbles.

In the Vale of Wardour there is a similar series, but not more than 110 feet thick, though all three divisions are represented. At the base of the Lower division there are tufaceous (? freshwater) limestones with a "dirt-bed" containing remains of Cycads; but the succeeding beds are brackish-water deposits, containing dwarf species of *Cardium*, *Corbula*, and *Perna*, and some of the beds show sodium-chloride cavities. The Middle group are alternating marine, brackish, and freshwater beds, some of the limestones consisting mainly of Cyrena shells and cases of entomostraca; others are compact marly stones containing remains of fish, insects, and plants; and there are one or two beds which are purely marine, containing well-grown shells of *Trigonia*, *Ostrea*, *Cardium* and other species. Still higher there is a freshwater series of marls and shelly limestones containing *Cyrena*, *Paludina*, and *Unio* shells.

This succession seems to indicate first a steady uplift of the Portlandian sea-floor, till part of it was converted into a land-surface with pools in which tufa was deposited. The upheaval, however, was not maintained, and the area sank till it was invaded by the sea and became a large lagoon of salt water. Then streams running off the surrounding land made the water brackish, and sometimes nearly fresh, but still there were occasional invasions of the sea until renewed upheaval finally raised the whole region above sea-level, and converted it into a permanent freshwater lake.

Northward, beyond the Vale of Wardour, the Purbeck Beds are, for the most part, concealed beneath the overstep of the Cretaceous strata, but there is good reason to believe that they extend continuously through Wilts and Berks, for they are exposed at Swindon and at Garsington in Oxfordshire, and they crop out again near Aylesbury and Whitchurch in Bucks. At these places, however, only the Lower Purbeck is found, and the beds seen are less than 30 feet thick. No doubt higher beds originally existed, and may still exist beneath the Gault and Chalk to the eastward, but there is no evidence that the series ever extended to the north of Leighton Buzzard.

With regard to their easterly extension from Dorset and Wilts, we may assume that they underlie the whole of Hampshire and Sussex, for they reappear in the eastern part of the latter county near Brightling and Battle. Moreover, they are no less thick than in Dorset, being estimated at 400 feet, and at Penshurst they seem to be even more, but they thin rapidly to the east (see p. 281). The lower beds consist of shales, limestones, and marls with some thick beds of gypsum. The higher beds are shales, with layers of shelly limestone and calcareous sandstone. The fossils found seem to indicate the usual alternations of brackish and freshwater beds.

Recent borings in Kent have afforded valuable information as to the eastern extension of the Purbeck and Wealden Beds in Kent, but unfortunately the published accounts cannot be relied upon, for in some of them the existence of Purbeck Beds has been altogether overlooked. By the kindness of Messrs. Lamplugh and Kitchin, however, I am able to state that at Pluckley not only are Purbeck Beds present, as might really be inferred from the record already published, but that they are about 100 feet thick. At Hothfield, to the eastward, they have not yet been separated from the Wealden, but judging from the published account the base of the latter may be put at 700 feet, which leaves a thickness of 92 feet to the Purbeck Beds. At Brabourne, 5 miles east of Ashford, they are still thinner; their upper limit is difficult to fix, but Mr. Lamplugh assigns them a thickness of from 56 to 68 feet. At Barham to the northward they appear to be absent, nor do they exist at Dover, but this may be due to the unconformity between the Jurassic and Cretaceous series at those places.

With regard to the northern limit of the Purbeck Beds below Kent and Surrey much less is known. They are in full force at Penshurst in the south-west of Kent, but they must thin out northward under the line of the North Downs, and may be cut off there by the basal-plane of the Vectian Beds, for at Chatham the latter rest directly on Oxford Clay. Purbeck Beds are also absent below Streatham in Surrey, where a boring proved the Gault to rest on Great Oolite.

How far the Purbeck area of deposition extended southward under the Channel and the Paris basin is unknown, for nothing higher than equivalents of our Portland Beds are exposed in the Boulonnais or in the Pays de Bray. At the same time it is quite possible that our lagunic and lacustrine series passed southwards into marine beds, which have been completely removed during the interval represented by the unconformity of the Cretaceous rocks, wherever they rest on Portland Beds round the Paris basin.

B. *Physical Geography of Upper Jurassic Time*

Some of the contrasts between the Bathonian and the Oxfordian deposits have already been mentioned (see p. 277). Once more we have a complete change in the character of the sediment, and as the phenomena exhibited are exactly in reverse order to those of the change from Lias to Oolites, we may assume that they were caused by movements of precisely an opposite kind, and that the epoch of the Oxford Clay was produced by a general and equable subsidence of the whole region from the very south of England to the extreme north of Scotland.

In this great deposit of dark blue clay we seem to have a repetition of Liassic conditions, and it is highly probable that the source of supply was the same—namely, the Coal-measures which once covered so large a portion of the British region. However this may have been, it is clear that submergence resulted in the introduction of mud-bearing currents which spread their load of sediment over the whole Anglo-Gallic area of deposition, destroyed the limestone builders of the Bathonian sea, and converted its clear waters into a "black sea" of mud-laden waves.

It is probable that the large Anglo-Belgian island, which remained above sea-level in Bathonian time, consisted partly of Carboniferous strata troughed in between broad anticlines of the older Palæozoic rocks. The platform of such rocks which now lies under our eastern counties is but the base which supported a higher superstructure in Jurassic times. Some of this superstructure must have been removed during the Oxfordian subsidence, and may have contributed largely to the Oxfordian deposits, for the planation may have cut down to the Silurian shales and the slates of Cambrian or Ordovician age, all of which would disintegrate into dark muddy sediment.

The episode of the Corallian Beds marks a time when from some cause the deposition of mud ceased over certain parts of the sea-bottom, and the water became clear enough for the growth of coral-reefs with their accompaniments of calcareous sands, marls, and oolitic limestones. This change was nearly as wide-spread as that of the Inferior Oolite, and it brought back similar conditions over the greater part of the region, except that the east and west ridge across England was deeply submerged. Whether it was due to a repetition of unequal movements, or simply to an interval of stationary conditions, is hard to say. It is, indeed, very difficult to give a complete and satisfactory explanation of these repeated alternations of argillaceous and calcareous formations, each of which spreads over the greater part of the Anglo-Gallic area of deposition.

It may be remarked that the succession of beds in Sutherland lends some colour to the idea of upheaval in the north during the Corallian epoch ; there as elsewhere the Oxfordian clays and shales tell of submergence, but the overlying sandstones (see p. 278) show that the currents were able to carry sand farther out from the shore, and over the deep sea mud, as they might do if the land was stationary or rising, and if the depth of the sea was gradually lessened by the accumulation of deposit in the manner explained by Mr. Godwin-Austen.[1] In the succeeding series of alternating marine and estuarine beds we trace the progress of a further subsidence. It is possible, therefore, that the intercalation of white sandstones in the shallow waters of the Scottish area, and of calcareous grits in the deeper water of the English sea, were due to one and the same cause.

In the stratigraphy of the Kimeridge Clay we find evidence of the commencement of another change. If we only regarded the thickness of this clay in the southern counties, we might suppose that the Jurassic subsidence reached its deepest limit at this epoch ; but when we remember that the clay diminishes from about 1000 feet in Dorset to only 100 in Oxfordshire, we must infer that the subsidence which permitted so much sediment to accumulate in the former county was not a general uniform movement, but was much greater in some districts than in others. There were, in fact, differential movements, resulting in the formation of two deep basins separated by shallower water over part of that tract which had been shallow water at the epoch of the Inferior Oolite (see p. 272).

Eventually a reverse movement set in, the supply of mud grew scantier, and the argillaceous sands which underlie the Portland Stone mark the effect of the incipient uplift of the whole region. The Anglo-Belgian island was again raised above the sea, and in the British area the sea-space between it and the western land was so contracted that only a shallow strait remained to connect the northern and southern Portlandian seas, as represented in Fig. 46 ; indeed, it is possible that this strait was closed toward the end of Portlandian time, and the two seas completely separated by an isthmus of greater or less breadth.

It is clear, at any rate, that the sea was contracted into two parts, which were practically separate seas ; the sea of the Portlandian limestones lying wholly to the south of Bedfordshire and opening southward through France, while a northern sea

[1] See *Quart. Journ. Geol. Soc.* vol. vi. p. 82.

extended from Germany into Yorkshire and Lincolnshire, and possibly through these counties for some distance westward, though how far westward we shall perhaps never be able to say. It is well, however, to bear in mind the possibility that the Portlandian sea may have reached westward into what is now the basin of the Irish Sea.

Finally, in Purbeck time there was a further uplift of the whole region. The southern area of deposition became a land-locked basin surrounded by land on the west, north, and east, though it may still have opened narrowly to the south-east through France into the Tithonian sea of Switzerland and Southern Europe.

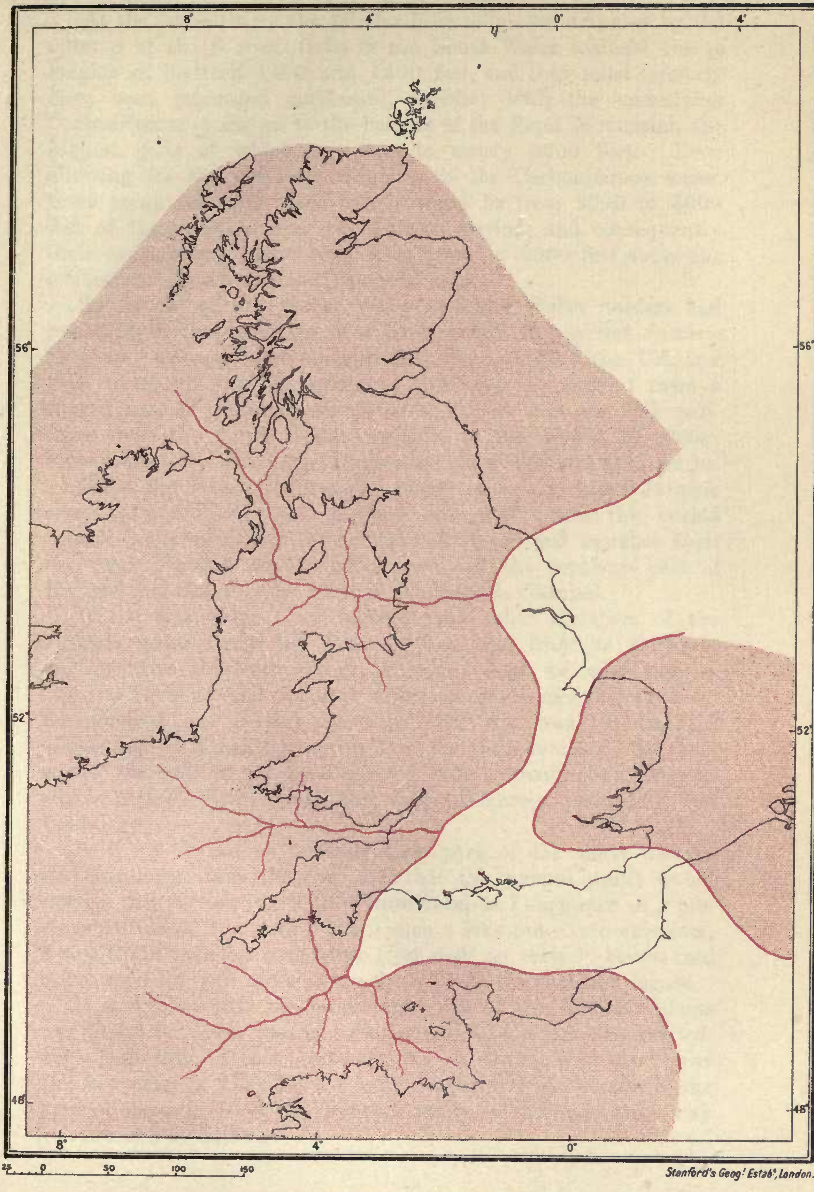
We have now brought the history of the British Jurassic sea to a close, and have arrived at the epoch of the great Purbeck-Wealden continent, which was to some extent a resuscitation of the Triassic continent, but with very different climatic conditions. Before we pass on to the history of the Cretaceous period let us endeavour to realise something of the general aspect and physical geography of the British region during the interval between the two periods.

In the first place, if anything like the Atlantic Ocean existed in Jurassic times its eastern shore must have lain far to the west of France and Ireland, so that these countries were joined to one another and to England. The hilly Palæozoic areas of Cornwall, Devon, and Wales doubtless formed high ground as they do now, but the Jurassic strata must have covered much of the lower ground, especially in Mid-Devon and over the area of the Bristol Channel.

The nearly horizontal position of the Lias in Glamorgan, or rather the absence of a continuous easterly dip, seems to show that this district did not participate in the easterly tilt which was given to the country east of the Severn valley. If we bear in mind that the escarpments of the South Wales coalfield must then have been much more lofty, and that the total thickness of the Jurassic series was certainly less near its shore-line than along its present outcrop, we shall feel sure that the Kimeridge Clay did not overtop the Carboniferous escarpments. To make this clear it is worth while forming a rough estimate of the thickness of the Jurassic deposits on the South Welsh border, and I think the following will be regarded as a reasonable apportionment :—

	Feet.
Kimeridge Clay	about 500
Corallian	,, 100
Oxford Clay	,, 300
Middle Oolites	,, 250
Liassic series	,, 300
	1450

Fig. 46.—GEOGRAPHY OF PORTLANDIAN TIME.



London : Edward Stanford, 12, 13 & 14, Long Acre, W.C.

At the present time the tabular hills or plateaus formed by the outcrop of the Pennant Grits in the South Wales coalfield rise to heights of between 1400 and 1800 feet, and they must formerly have been prolonged northward, together with the underlying Carboniferous strata, on to the heights of the Black Mountains, the highest parts of which now rise to nearly 3000 feet. Even allowing for the northerly thinning of the Carboniferous series, these mountains must have been covered by from 2000 to 3000 feet of these beds during the Jurassic period, and consequently their summits must have been from 5000 to 6000 feet above the lowlands of the Cardiff and Bridgend area.

So far as we can judge, Wales and the Welsh borders had remained in the condition of a land surface throughout Jurassic time, and we may safely assume that the valleys of the Usk and Wye were not then in existence, but that in place of them a rugged mass of Carboniferous rocks stretched over the Usk pericline from the South Wales coalfield to the Forest of Dean; broken probably into lofty escarpments above the anticlinal ridge.

From the Welsh borders the plains of newly-raised Jurassic strata extended over the Midland area and across the buried eastern land, separating the northern lowlands and marshes from the great Purbeck lagoon which occupied the southern part of England and the adjacent parts of the English Channel.

If the Kimeridge Clay followed the other members of the Jurassic series across the Pennine area, and from its thickness in Yorkshire this seems very probable, then we may suppose that the Portland and Purbeck uplifts simply raised the whole of the northern and north-western gulf into dry land, the drainage of this land still making its way into the Germanic sea. In other words, the gulf would be converted into a broad plain through which a large river would flow eastward across Lancashire and Yorkshire.

It is by no means unlikely that part of the north-western gulf was deeper than the rest, and that the general uplift would convert this portion into a freshwater lake, as I suggested in a previous edition of this work; but if such a lake came into existence, I now think that the outflowing river took an easterly course into the eastern sea, and not a southerly one into the southern lagoon.

It is possible that the more rapid rise of the Midland plains was due to the lesser load of Jurassic sediment which they carried. Some indication of this has been given in the table of the Upper Jurassic series (p. 279), but the total comparative thicknesses of the Jurassic deposits below the Purbeck group in the three areas may be estimated as follows:—

	Dorset.	Midlands.	Yorkshire.
Upper Jurassic . .	2000	630	1000
Middle Jurassic . .	850	140	450
Liassic series. . .	900	700	1050
	3750	1470	2500

It is curious that these figures seem exactly proportionate to the differences of level which we have reason to think actually subsisted in Purbeck time—namely, a lagoon below sea-level in the south, a lowland only just above sea-level in the north, and an intervening isthmus which was well above the level of both.

As to the climate and vegetation of this land there is nothing to show that it was of a tropical character ; the frequent occurrence of coniferous wood in Purbeck and Wealden Beds indicate that on its higher portions conifers were the prevalent trees, while the existence of cycads and the abundance of long reed-like leaves and of insect remains are evidence that near the lakes the air was warm and moist, engendering a thick vegetation, in which many kinds of reptiles found a congenial habitation.

CHAPTER XI

THE CRETACEOUS PERIOD

THE areas occupied by rocks of Cretaceous age in the British Isles are small when compared with those of the Triassic or Jurassic systems, though the later Cretaceous deposits may originally have covered a larger area than either of the older series. The main mass of them lies in the S.E. of England, the outcrop of their lower members running from the coast of Dorset to the western side of Norfolk, and then below the Wash through Lincolnshire and Yorkshire to Speeton Bay. Outliers in Devonshire which rise to a height of 900 feet in the Haldon Hills show that they must have extended far out to the western land, but no relics of them are left in the N.W. of England, though the higher members of the system must certainly have been there, since they occur in Ireland and on the west coast of Scotland.

The relation of the Cretaceous strata to the underlying formations is an important matter. Throughout the greater part of England there is a decided unconformity between the Cretaceous and Jurassic systems, and even in Yorkshire the apparent conformity at Speeton is deceptive, for the lower beds thin out westward and the higher beds overstep them, as well as several members of the Jurassic series. It is only in the south of England that a complete and conformable sequence is found, but these connecting deposits are of freshwater origin, and do not bridge the gap in the marine succession.

This gap was caused by the elevation of the greater part of the British region into dry land, and it was only after a long period of time, during which several thousand feet of marine deposits were accumulated in the South European region, that parts of this land were again submerged, and that the sea once more spread across the centre of England.

The Cretaceous system is divisible into two series of deposits, a lower and an upper, each of which comprises several stages.

The following is a tabular view of the members of the system, as developed in the north and south of England respectively, with the names of their continental equivalents :—

		Northern Area.	Southern Area.	France and Switzerland.
Upper Series.	8.	Wanting	Wanting	Danian
	7.	Upper Chalk	Upper Chalk	Senonian
	6.	Middle Chalk	Middle Chalk	Turonian
	5.	Lower Chalk	Lower Chalk	Cenomanian
	4.	Red Chalk	Selbornian	Albian
Lower Series.	3.	Speeton Clay, upper	Vectian	Aptian
	2.	Speeton Clay, lower	Wealden	Barremian
	1.			Neocomian

As in previous chapters, it will be convenient to deal first with the time represented by the Lower series, and then with that of the Upper series and the great Cretaceous subsidence.

1. Lower Cretaceous Time

A. *Stratigraphical Evidence*

Since the freshwater Wealden Beds succeed the Purbeck series conformably in the south of England, it will be convenient to take that area first.

1. Wealden Beds.—These beds are restricted to certain areas in the south of England, and do not extend far beyond the limits of the Purbeck Beds. They occupy the country known as the Weald of Kent and Sussex, and pass beneath the chalk hills which surround this district; but they do not extend far to the north, for the deep borings at Chatham, Streatham, and Richmond proved their absence at those places. Eastward they reach below the Straits of Dover into the Boulonnais, and westward they spread beneath Hampshire and the Isle of Wight into Dorsetshire, but have not been traced beyond Osmington and Ridgeway. Southward they do not seem to have reached so far as Normandy, for they do not appear below the outcrops of the Aptian in that part of France.

The Wealden Beds consist of thick lenticular alternations of sand and clay, the sands being thickest in the lower part and the clays in the upper part, so that they are usually divided into the Hastings Sand and the Weald Clay. In the lowest beds (Ashdown Sand) layers of lignite are not unfrequent; the Wadhurst Clay also contains lignite as well as nodules of clay ironstone. In the sands near Cuckfield and Lindfield there are thin layers of conglomerate, the pebbles in which are largely derived from Palæozoic rocks, and were probably brought down by streams draining off the land to the north; and this is interesting as showing that streams had already cut down through the Upper Jurassic clays to the Palæozoic rocks of that region. The Weald Clay consists of clays and shales with local beds of sandstone and many layers of shelly limestone, the last consisting largely of *Paludina* shells, and thus resembling the Upper Purbeck limestones.

The fossils of the Wealden are entirely freshwater and terrestrial, plant remains, minute Crustacea, freshwater mollusca, fish and reptile bones occurring throughout; and there is no admixture of marine species, except at the very top of the series in the Isle of Wight.

In the western part of Sussex the Wealden Beds are about 1800 feet thick, the Hastings Sands and Weald Clay being nearly equal in thickness. When followed eastward, however, both become much thinner, and along the eastern outcrop in Kent they are not more than 800 or 900 feet thick. In the boring at Pluckley the base of the Wealden appears to occur at a depth of 1000 feet, and about 100 feet more must be added for higher beds cropping out north of the boring.

At Hothfield, near Ashford, the Weald Clay was entered at 180 feet from the surface, and extends to 580, according to Professor Dawkins's account. Below this are sands and sandy clays, which he did not separate from the Purbeck series, but as a bed of white sand rests on dark clays with calcareous bands at 700 feet, this is probably the plane of division, and gives the Wealden Beds a thickness of 520 feet. At Brabourne Mr. Lamplugh, who has examined the cores, refers a thickness of only 56 feet to the Wealden. At Swingfield it rests on Kimeridge Clay, and is considered to be 130 feet by Mr. Burr; in the Dover boring it has not yet been properly determined, but is not more than about 80 feet, and at Fredville Mr. Burr believes that it has thinned to 35 feet, and that it there rests on the Corallian.

From these borings we learn that the Wealden Beds overlap the Purbeck and overstep the Portlandian and the Kimeridge Clay till they rest on the Corallian. This transition from a conformable to an unconformable relation can only be accounted for by a subsidence of the area surrounding the Purbeck-Wealden lake, allowing its waters to cover a larger area than those of the Lower Purbeck lagoons. No doubt this subsidence was part of the general subsidence which led to the invasion of the Vectian sea; but it must have been more rapid below and around the lake-area, producing a geosyncline and an inward inclination of the Portland Beds and Kimeridge Clay, so that their basset edges were truncated by the waters of the overspreading lake.

That the same overstep takes place northward through Kent is almost certain, though at present there is not such ample proof of it. Still, at Barham, 5 miles north of Swingfield, the Wealden (only 65 feet thick) rests on Corallian. It is remarkable, however, that at Maidstone there appears to be over 900 feet of Wealden Beds, the boring at Foley House not reaching their base, while at Chatham, only 8 miles to the north, there are none. From this we must conclude that the northern shore of the lake was steeper than the eastern, and perhaps that the pitch of the post-Purbeck syncline was greater.

Passing now to the western part of the lacustrine area, we find the beds to be even thicker in the Isle of Purbeck than they are in Western Sussex, for at Swanage they are estimated to be 2350 feet thick. Westward, however, they decrease rapidly to 1200 at Worbarrow Bay, and 750 at Mupe Bay. They can be traced as far as Upway near Weymouth, where the thickness seen was 350 feet; but it may have been more before it and the Vectian were cut off by the overstep of the Gault. Probably they thinned out westward between Abbotsbury and Bridport.

Wealden Beds are found again in Wiltshire (Vale of Wardour), but are not more than 60 or 70 feet thick at Dinton, and they disappear westward below the Vectian sands. Northward they probably thin out below Salisbury Plain. It is true that freshwater deposits occur in Oxfordshire, but they rest unconformably on Purbeck and Portland Beds and appear to pass up into marine beds of Aptian age; consequently it is probable that they form a freshwater episode in the Vectian group.

2. Vectian Beds.—These are entirely marine and mark the incursion of the outside sea into the area of the great Wealden lake; their lower beds, however, do not extend far beyond the limits of the Weald Clay, but their highest beds have a much wider extension. The group has long been known as the "Lower Greensand," but no one can defend the continued use of this awkward and inaccurate appellation, nor adduce any good reason against the adoption of the name Vectian, which is only a modification of the term Vectine proposed by Fitton in 1845 as a name for this set of beds.

The Vectian group is most completely and clearly exposed in the Isle of Wight, where it is divisible into four portions: (1) Atherfield Clay, 60 to 90 feet; (2) Walpen or Ferruginous Sands, 500 feet; (3) Shanklin Sands, or Sand-rock group, 200 feet; and

(4) the Carstone of Mr. Strahan.[1] They are the deposits of a shallow sea, rather deep and muddy at first, but becoming shallower afterwards. The basement bed of the Atherfield Clay is a seam of coarse grit containing small pebbles, with the teeth and bones of fishes; of this Mr. Meyer remarks: "It is just such an accumulation of sediment as would result from the dispersion of shore-deposits over the floor of a moderately deep lake. The fish-bones are those possibly of inhabitants of the Wealden waters, and their presence at the junction of the two formations may be due to the suddenness of their destruction by the change from fresh to salt water."

The Atherfield Clay is a deposit slowly accumulated in still water of some depth, and does not vary in thickness so much as the other divisions. The overlying group of sands and clays is very variable in character and thickness. The Sand-rock series consists of current-bedded sands, with laminated clays and occasional layers of small pebbles; it is evidently a shallow-water deposit, while the presence of lignite and carbonaceous matter seems to show that the currents were caused by inflowing rivers. All these beds are thickest to the south, and thin to the north-east and north-west.

The Carstone is a coarse pebbly grit, the pebbles being often more than half an inch long; unlike the lower divisions, it thickens toward the east, and Mr. Strahan regards it rather as the basement bed of the Gault than as the highest member of the Vectian division.

When followed westward through Dorset the Vectian Beds rapidly diminish in thickness, being only 200 feet thick near Swanage and less than 70 at Mupe Bay, beyond which they are not seen. They suffered some erosion before the deposition of the Gault, and may originally have extended quite as far as the Wealden, *i.e.* nearly to Bridport.

In the Wealden area the Atherfield Clay still forms the basal member of the series; the Hythe and Sandgate Beds correspond to the Ferruginous Sands and the Folkestone Beds with the "Sand-rock" group. The Hythe Beds often contain small pebbles of Palæozoic rocks, and near Maidstone fragments of red granite also occur in these sands. The whole group thins gradually from west to east, having a maximum thickness of 450 feet near Petersfield and Godalming, while at Sandgate it is not more than 240 feet. At Dover it has diminished to about 128, and at Fredville, still farther east, Mr. Burr gives its thickness as only 52 feet,

[1] See "Geology of the Isle of Wight," by A. Strahan and C. Reid, *Mem. Geol. Survey* (1890).

though the Atherfield Clay seems to be still represented at its base.

At Maidstone the thickness of the Vectian is about 270 feet, but at Chatham, only 8 miles north, it has shrunk to about 40 feet and rests on Oxford Clay. Again, in Surrey, near Merstham and Nutfield, the thickness of the group was estimated by Topley to be 390 feet, but a boring at Streatham, 12 miles north of the outcrop, found the whole of this to have thinned out, the Gault there resting on a representative of the Great Oolite (Bathonian). From these facts it is clear that the whole group thins rapidly under the North Downs and less rapidly eastward, passing beyond the east coast of Kent, but probably not far beyond. In the Boulonnais the Lower Cretaceous series is represented by a very meagre set of deposits, the coast section showing only 100 feet of ferruginous sands with freshwater fossils, overlain by 20 or 30 feet of clay and sand with marine fossils. The first is generally regarded as Wealden, and the higher beds represent the Vectian, but both thin out inland toward the east, proving that the shore of the Vectian sea was not far off in that direction.

Returning to the western area the Vectian must thin very rapidly northward under Hampshire, for though it does appear above the Wealden at the eastern end of the Vale of Wardour, in Wilts, it is there less than 50 feet thick. The revised mapping of that area has shown that the Vectian oversteps the Wealden, and is itself cut off by the sandy and pebbly base of the Gault. Hence we may conclude first that some of the lower beds are missing, and secondly, that the highest beds may also be absent. Now a special feature in the local group is, that it mainly consists of grey and yellow sands with layers of chert and cherty sandstone. These sands resemble the Hythe Beds of Western Sussex more than any other member of the series, and I am therefore inclined to regard the beds seen in the Vale of Wardour as a representative of the Hythe division. Further, I think that they were originally covered by representatives of the Sandgate and Folkestone Beds before the deposition of the Gault, and that these higher beds would be found beneath the Gault if a boring were made near Salisbury.

When next seen in North Wilts and Berks, the group presents a different facies, consisting of brown ferruginous sands, with occasional beds of conglomerate which contain a curious mixture of pebbles—rounded pebbles of quartz, banded slate, hornstone, decomposed limestone, and chert. These beds appear to be the equivalents of the Folkestone and Bargate Beds of the Weald; they have clearly been formed in shallow water, near shore, and under the influence of strong currents, for some of the pebbles are two or three inches long.

The source of these pebbles is an interesting subject of inquiry. The larger pebbles cannot have travelled far, and, indeed, most of these have been derived from the neighbouring Jurassic rocks. As to the quartz and slate pebbles, it does not seem likely that they were derived directly from the Palæozoic rocks, because the localities are so far distant from areas of Palæozoic rock that were likely to have been exposed; and for the same reason it is unlikely that they came from the Trias. They may possibly have been derived from shore-beds of Portlandian age, for similar pebbles occur in the Portland sands of Wiltshire; but it is probable that the chief sources of supply were accumulations of pebbly sand and shingle brought down by streams during the terrestrial conditions of the Purbeck and Wealden epochs, and deposited in the valleys of the rivers which ran through the plains surrounding the Purbeck-Wealden waters. Some rivers would rise in the areas of Palæozoic rock which existed both in the east and in the west, and they may have carried large quantities of sand and pebbles on to these plains during times of heavy rain, and such deposits would be rearranged by the advancing waters of the Vectian sea.

These Pebble Beds extend as far as Baldon, south of Oxford, but near Garsington and Shotover a very different set of beds come in, the characters of which more resemble those of the Wealden Beds; they consist of variously coloured sands and clays, with beds of iron-ochre and fullers' earth, and they contain freshwater shells (*Cyrena*, *Unio*, and *Paludina*), with pieces of coniferous wood. Similar beds occur on outliers near Brill, Quainton, and Whitchurch, while south of them, and in close proximity to the outcrop of the Gault, are other beds in which marine fossils have been found. The relations of these two sets of beds are not absolutely clear, but I agree with Dr. A. M. Davies in thinking that the marine beds overlie the others.[1]

The Upper Vectian sands next appear near Leighton and Woburn, where they are 200 feet thick, and consist chiefly of yellow and white sands, with Carstone at Leighton and fullers' earth near Woburn. Near the base is a remarkable seam of phosphate nodules, with derived fossils (chiefly from Upper Jurassic strata), and pebbles of quartz and chert like those of the Berkshire Beds. The sands are current-bedded, and the inclination of the layers is most often south or south-eastward, showing that the prevalent currents came from the north. Similar beds with

[1] *Proc. Geol. Assoc.* vol. xvi. p. 53.

layers of nodules stretch through Bedfordshire and Cambridgeshire as far as Ely.

The contents of the Bedfordshire Pebble Beds have been carefully studied by Mr. Teall and Mr. W. Keeping. The rock-fragments form an interesting assemblage, and include :—

1. Dark-brown ferruginous grit, with fossils of the northern marine "Neocomian" or Speetonian series.
2. Limestone and chert from Jurassic strata, especially from the Portlandian and Kimeridge Clay.
3. Vein-quartz, chiefly as small well-rounded pebbles.
4. Quartzites and hard sandstones of several kinds.
5. Yellowish fine-grained argillaceous sandstone.
6. Black chert from Carboniferous limestone.
7. Flinty argillites (lydianstone).
8. Pale slate with Lower Silurian (Ordovician) fossils.

Some of these rocks have been derived from local Jurassic Beds, but others can apparently only have come from the north, or from concealed outcrops to the north-east, while the rest are such as might be derived from the buried Palæozoic area in the east of England. Most of the pebbles are rounded and water-worn, but some are quite angular, and can hardly have travelled very far. The supply was probably derived in part from the erosion of the eastern land by the sea and in part from pre-existent beds of river gravel, as already suggested.

Now it can be seen from any geological map which shows the outcrops of the Oxford and Kimeridge Clays, that the maximum amount of unconformity between the Jurassic and Cretaceous systems is along a tract on the borders of Bedford and Cambridge where the Vectian sands rest on the Oxford Clay. South-west and north-east of this area it lies on the Kimeridge Clay, and in reality there is a gradual overstep of the Cretaceous base from the Portlandian and Kimeridgian of Buckinghamshire on to the Ampthill Clay, which represents the Corallian, and thence on to the Oxford Clay; there is also a similar transgression from the north-east. Moreover, careful study of the map will show that the position of this axis of uplift coincides with a change in the direction of the strike of the Jurassic rocks, which to the north of it strike nearly due north and south, while south of it the direction is N.E. and S.W.

As these facts are not clearly shown on the maps of the Geological Survey, because the Ampthill Clay is not separated and because of the concealment of outcrops by Drift and Alluvium, I am glad to avail myself of a map designed by Mr. R. H. Rastall on purpose to show them (Fig. 47). Mr. Rastall thinks[1] that the axis of elevation was a "posthumous" continuation of the Charn-

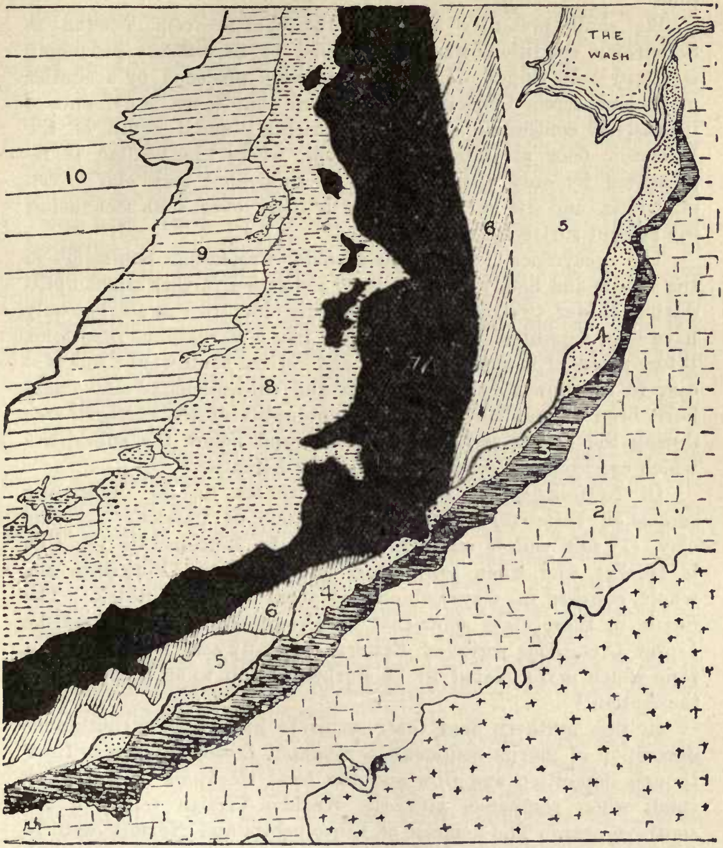


Fig. 47.—MAP SHOWING THE OUTCROPS OF THE JURASSIC AND CRETACEOUS FORMATIONS BETWEEN BUCKINGHAM AND LINCOLN (R. H. Rastall).

1. Eocene.
2 Chalk
3. Gault (clay).
4. Vectian sands.
5. Kimeridge Clay.
6. Ampthill Clay.
7. Oxford Clay.
8. Oolitic limestones, etc.
9. Lias.
10. Keuper marls.

wood axis, and that its direction was from N.W. to S.E. While fully admitting the probability of such posthumous movements

[1] Cambridgeshire, etc.: "Geology in the Field," p. 141, *Geol. Assoc.* (1909).

in Jurassic and in later times, I think that the evidence does not favour the view that they also occurred in Cretaceous time.

We shall presently see that the change from Vectian to Selbornian conditions was accompanied by movements producing east and west ridges. I think these were preceded by a similar movement across Central England, and that there is evidence of its easterly continuation in the surprisingly small depth of the Palæozoic floor at Culford in Suffolk, where the Vectian is represented by only about 30 feet of calcareous rock and brown sandstone, and its surface is only a little over 600 feet below the present surface of the ground.

The occurrence of fragments of older Cretaceous sandstones in the Potton and Sandy Beds seems to indicate a further slight uplift during Lower Cretaceous time, for this older rock must not only have been deposited, but consolidated into a ferruginous sandstone, before pieces of it were broken off and carried southward ; nor is it easy to see how this consolidation and subsequent erosion could have been accomplished without some uplift of the northern area during the earlier part of the period and before the subsidence which carried the Vectian sea across the isthmus.

In Norfolk different beds begin to set in, the descending succession being (3) ferruginous sandstone or Carstone, (2) blue clay, (1) soft yellow and white sand. In Lincolnshire the clay is thicker, and when seen again at Speeton in Yorkshire the whole consists of clays which are about 200 feet thick. The fossils in these clays show that they represent the whole marine Lower Cretaceous series of Eastern Germany and Russia, from a zone which is considered to be Purbeckian up to an equivalent of the Aptian.[1]

In this northern area there seems to have been a continuous deposition of marine sediments throughout Lower Cretaceous time, though deposition was slow and the total thickness of beds very small when compared with the Wealden-Vectian series of the southern area. The deposits of Lincolnshire and Norfolk seem to have been formed in a large shallow bay ; those of Speeton indicate deeper water, or at any rate a greater distance from the shore-line, and the Germanic sea probably stretched far to the northward of that place.

It may indeed have extended between Scotland and Scandinavia, for remnants of a Lower Cretaceous rock have been found near Aberdeen. The evidence of this consists of fragments and layers of a greenish-grey glauconitic sandstone embedded in the Glacial

[1] See Messrs. Lamplugh and Pavlow, *Bull. Soc. Imp. Nat. Moscou* (1892).

Drift of Moreseat, north of Cruden Bay.[1] They are so numerous and the rock is so brittle that they cannot have travelled far, and the fossils found in them seem to indicate equivalents of the Barremian and Aptian stages of the Continent. Another patch of Lower Cretaceous sand has recently been found in Caithness, and probably belongs to a still lower part of the series.

To conclude this brief survey of the stratigraphical evidence we must take note of the subterranean extension of the Vectian sands beneath the eastern counties. They seem to extend for some distance below the counties of Lincoln and Norfolk, for borings have proved their presence at Skegness and at Holkham Hall, near Wells, in Norfolk, so that it is probable that they underlie the central part of the North Sea and the whole of Norfolk. In Suffolk, however, they soon thin out against the older rocks. Thus, though the sands are known to occur in full force below Cambridge and Soham, they are reduced to a few feet of sandy clay and calcareous sandstone at Culford (see p. 300), only 13 miles east of Soham, and these beds rest directly on Palæozoic rock, proving that all Upper Jurassic strata had been removed in the Purbeck-Wealden interval.

At Ware in Herts there is no representative of the Vectian, nor was it found in the borings at Cheshunt and Loughton; but at Richmond, near London, 10 feet of sandy and shelly limestones were found to intervene between the Gault and the Great Oolite, and their basement-bed is a conglomerate of various rock-fragments and fossils, mingled with phosphatic nodules. The matrix of this conglomerate is largely derived from the Oolitic limestones on which it lies, but most of the pebbles and subangular fragments have come from Palæozoic rocks which must have been *in situ* at no great distance, and from the surface of which the Upper Jurassic Beds must have been removed.

It is doubtful whether any Vectian rock was traversed by the boring at Meux's Brewery in London, but it is certain that none exists either at Kentish Town to the north, or at Streatham to the south; at Rochester, however, sands again come in between the Gault and Oxford Clays, and it is also present below Winkfield near Windsor, so that we get an approximate limit for the area covered by Vectian deposits below the overlapping Gault.

B. *Physical Geography*

We have seen that at the close of the Jurassic period the greater part of England presented the aspect of a fertile lowland country;

[1] See *Geol. Mag.* for 1898, p. 21.

bordered on the west by the highlands of the continental land, of which Ireland is merely a remnant, and from which two broad peninsulas must have projected eastward : a southern promontory, including Cornwall and Brittany, and a more northern one passing through Wales into Monmouth, Hereford, and Shropshire. Between these peninsulas stretched plains formed by the upraised floors of the Jurassic gulfs which had occupied the Bristol Channel and the Irish Sea.

We have also supposed that the Pennine ridge of Permian and Triassic times was completely buried beneath the Jurassic deposits, and that the north-western gulf of the Jurassic sea when raised into land sloped gently across this Pennine area and drained into the sea which still remained to the east of Yorkshire.

South of this northern lowland and the Germanic sea the plains extended from the Welsh border to beyond the line of our present eastern coast, and farther south similar plains stretched from Brittany on the west to the Ardennes in the east; while in the midst of these great veldt-lands lay the broad expanse of the Purbeck-Wealden lake.

The essentially lacustrine character of the Wealden deposits is now generally admitted. By some geologists they have been regarded as the delta of a great river, comparable to that of the Nile or the Mississippi ; but as a matter of fact the deposits do not resemble those of a single delta, but rather those of several rivers or streams pouring their sediment from different directions into a large freshwater lake. This view of the Wealden deposits was held by S. V. Wood and by Godwin-Austen, and was strongly advocated by Meyer in 1872, who remarked[1] that although there is considerable variation in the Wealden deposits, "yet one might venture to say that nine-tenths of the whole was quietly accumulated. The fine-grained sandstone and quartzose grits of the lower beds, the stiff red clays of the middle, and thinly foliated 'marl with *Cypris*' of the Upper Wealden might all be of lacustrine origin, and yet include both tree stems and the bones of reptiles. There is indeed in these again, as in some portions of the Purbeck strata, a strong resemblance to the Tertiary lacustrine beds of Central France."

From the nature and fossil contents of the lower and middle beds, he infers that the waters were at first shallow and frequently disturbed by the currents of inflowing rivers; "the finely laminated strata of the Upper Wealden, are such as, on the contrary, belong to deeper waters, and rarely, if ever, show traces of disturbance." These considerations lead us to conclude that during

[1] *Quart. Journ. Geol. Soc.* vol. xxviii. p. 247.

the earlier part of the Wealden epoch the country was still rising, and that the Wealden rivers then attained their maximum velocity and carrying power; for a time perhaps the land was stationary, but subsidence quickly ensued, diminishing the river-action, increasing the area of the Wealden lake, and adding depth to its central waters.

The history of the Purbeck-Wealden episode may therefore be summed up as follows: the Purbeck series was formed during upheaval in lagoons that were gradually cut off from the retreating sea; the Lower Wealden Beds were formed in a freshwater lake on the site of the old lagoons, and the level of its waters was maintained by the influx of several powerful rivers; the Upper Wealden was formed during a subsidence which widened the area of the lake, and eventually depressed it beneath the waters of the returning sea.

The next point which calls for consideration is the drainage system of the Wealden land, and whether it is possible to ascertain the direction from which the principal rivers ran into the lake. It must be remembered that in passing from the Purbeck to the Wealden we find evidence of rapidly increasing fluviatile action, as if rivers which had previously carried little but matter in solution now became loaded with a quantity of detritus in suspension. It may be pointed out that in Purbeck times the valleys of the English and Bristol Channels were in all probability occupied by rivers of considerable size, but that on the first emergence of the land the amount of mechanically-transported detritus which they carried seaward seems to have been very small. Not only was the land at a comparatively low elevation, but it is also very likely that lakes existed in the upper reaches of the rivers, which would intercept and retain the detritus carried by the stream, just as the mud of the Rhone is intercepted and deposited in the Lake of Geneva.

As, however, elevation proceeded, and the land rose higher above the sea, rainfall would be increased, erosion would be accelerated, the load carried by the streams would be larger, the volume and velocity of the currents would be greater, and any lakes that existed would be rapidly filled up; under such conditions a larger quantity of detritus would be carried to the mouth of the rivers and poured into the Wealden basin. This would sufficiently account for the differences observable in passing from the Purbeck to the Wealden Beds.

If, however, these western rivers were the only streams that ran into the lake, we should expect the sandstones to diminish eastward, but this is not the case, the Lower Wealden of Sussex being more sandy than that of Dorset; and these Sussex sands must, I think, have been brought by minor streams which drained the land on the northern side of the lake—a supposition which finds confirmation in the Pebble Bed of Lindfield (p. 292). It is also possible that a stream may have entered the eastern end of the lake, for, as we shall presently see, its outlet is not likely to have been in that direction.

We may therefore conclude that the principal rivers flowing into the Wealden lake came from a westerly direction, draining the large tract of country which then connected Brittany and Cornwall with Ireland. Other streams of smaller volume, but carrying much detritus, flowed in on the north and north-east. To the position of the outlet we are guided chiefly by the disposition of the overlying beds; these marine (Aptian) deposits are continuous through the north-east of France from the Pays de Bray to the Haute Marne, and probably passed over the Côte d'Or to join those of Switzerland. Hence we may assume that this was the line along which the excurrent river ran from the Wealden lake, falling into a gulf of the Neocomian sea which then reached as far as the Haute Marne.

With regard to the size and extent of the Wealden lake we can form a fairly correct idea from the facts already stated respecting the area over which its deposits are found. The distance from Wissant near Calais to Weymouth in Dorset is 185 miles, and it is probable that the northern shore of the lake ran obliquely through Dorset, and that the greatest length of the lake lay entirely within what is now the area of the English Channel. In other words, the lake may have extended south-westward to about 3° west long., in which case its length would have been 225 miles.

To estimate its width from N. to S. we may assume that its northern shore passing under Salisbury Plain ran eastward by Andover, from which place to the south coast of the Isle of Wight is a distance of about 43 miles. We know that the lake did not extend to the opposite shore of France, but considering the great thickness of Wealden beds on our south coast, it is reasonable to suppose that they spread as far southward as they do to the northward. Now the distance from the Isle of Wight to the Cotentin (Pointe de Barfleur) is about 60 miles, and the lake may well have reached within 20 miles of that point, so that we may assume the average width across its central part to have been about 80 miles. On these suppositions the area occupied by the lake would be approximately that indicated in Fig. 48.

From the considerations already stated, it is probable that the actual river-deltas attained their maximum development in early

Stanford's Geog! Estab! London.

Fig. 48.—MAP SHOWING THE PROBABLE EXTENT OF THE WEALDEN LAKE.

Wealden times, while the land was rising or stationary, and the lake was comparatively shallow; but when the land began to subside erosion and transportation would be checked, though the volume of water filling the river-channels might still be large; the level of the lake-waters would probably rise, and the surface extent of the deltas would be greatly reduced, if they were not submerged altogether. Toward the close of the lake's existence this seems to have been the case, the shaly clays of the Upper Wealden indicating quiet deposition in the still waters of a lake that was being gradually lowered toward the level of the sea.

As already stated, the deposition of the Wealden Beds was contemporaneous with the formation of the marine Neocomian strata of France and Germany. The Germanic sea was extending itself westward, and a gulf connected with it lay over the eastern parts of Yorkshire and Lincolnshire. At the same time the southern Neocomian sea was gradually creeping north-westward up the valley of the river which ran from the Wealden lake, and the distance between the lake and the sea was gradually lessened, till at length the last barrier was broken through, and the Wealden lake became the Vectian gulf or estuary.

The change from the lacustrine shales of the Wealden to the marine clay of the Lower Vectian is a sudden one, and in this respect is like the change from the Triassic marls to the Rhætic Beds; but the actual conditions of the two cases were very different, the area of the Wealden lake was very much smaller, and its conversion into a gulf was not accompanied by the tremendous climatal change which took place in the earlier time, when the Triassic deserts were converted into fertile and forest-clad districts.

The land of Vectian time was doubtless similar in aspect and climate to that of Wealden time, and the plants and creatures which inhabited the country were the same. From the remains found in Wealden Beds we can picture the shores of the lake as clothed with an abundance of cycads and ferns, from among which coniferous trees rose at intervals to a greater height, while the marshy places displayed a rank growth of Equisetums (Mares-tails), Chara, and other water plants. On this vegetation browsed the huge Dinosaurian reptiles which are known by the name of *Iguanodon*, *Polacanthus*, and *Hylaeosaurus*, the first two of which seem to have resembled kangaroos in being able to support themselves on their massive hind-legs.

Fig. 49 is an attempt to portray the kind of scenery which the shores of the Wealden lake must have presented, with the plants and trees above mentioned and an *Iguanodon* in the midst of them.

Fig. 49.—IDEAL VIEW OF A LANDSCAPE BY THE WEALDEN LAKE.

For assistance in the composition of this scene I am indebted to Mr. Newell Arber, F.G.S., F.L.S.

The geography of the British area had now become similar to what it was in Portlandian time, *i.e.* there were two gulfs, one on the south, the other on the north of a central land barrier, but the gulfs were of very different shape. The southern gulf covered the site of the Wealden lake, and at first did not extend far to the north of it, and consequently not so far northward as the Portland and Purbeck waters had done. On the other hand, a gulf of the Germanic sea had established itself over the eastern parts of Yorkshire and Lincolnshire at the very beginning of Wealden time, and seems to have gradually extended itself southward into Norfolk before the Vectian epoch.

Moreover, the relics of Lower Cretaceous deposits in the N.E. of Scotland make it probable that the northern sea had broken through the Scoto-Scandinavian land-barrier, and had formed a gulf which reached northward into Aberdeen and Caithness, with possibly a still farther extension into the Arctic region.

For a certain time after the first invasion of the Wealden lake the land seems to have been nearly stationary, so that this basin was gradually silted up, and shallow-water conditions prevailed till further subsidence took place. Marine erosion, however, was active, and, aided by the subsidence, the sea spread farther and farther over the ground which separated the two gulfs, till at length the waves effected a junction across the lowest part of the intervening isthmus and invaded the lacustrine area, which seems at this time to have existed on the isthmus, and in which the Shotover sands were formed. The communication thus established became a narrow strait or channel, through which a strong current ran from the northern to the southern sea (see p. 297). This channel doubtless increased in width, but there is no evidence that the sea had encroached very far either on the eastern or western land before the formation of the Gault, which overlaps the Vectian sands in both directions. The western coast evidently consisted of Upper Jurassic rocks, and it is probable that the actual shore did not lie very far beyond the present limits of the Vectian sands, but ran in a N.N.E. direction from near the position of Oxford through the counties of Northampton, Rutland, and Lincoln.

We have seen that at the beginning of the Cretaceous period the eastern land was probably buried for some distance beneath the Oxfordian, Corallian, and Kimeridgian deposits; while at the close of Vectian time we find that all these deposits have been removed, and that where the Vectian exists under our eastern counties, as at Culford and at Richmond, it rests either on the Great Oolite or directly on the Palæozoic rocks. How is this to be accounted for?

In the first place, the Upper Jurassic Beds may have thinned considerably in passing eastward toward the shore-line of the Jurassic sea at that time. Secondly, the area was certainly undergoing subaerial erosion and detrition throughout the Portland, Purbeck, and Wealden epochs, so that there was time for the removal of much material. When, however, the floor of hard Palæozoic rocks was reached by the eroding streams, the rate of vertical erosion would be diminished, though the lateral erosion and general detrition of the covering Jurassic strata would still continue.

We must also remember that the Vectian sands may have originally spread farther eastward than their present limit beneath the Gault, wherever that is found to be; because, as we shall presently see, the Gault is more or less unconformable to the Vectian sands, and the eastern shore-line of these sands has been destroyed by the waves of the Selbornian sea, which formed a plane of marine erosion across all the older strata, whether Vectian, Jurassic, or Palæozoic.

There is no reason, however, to suppose that the Vectian sea ever encroached very far on to the surface of the Palæozoic rocks, and the probability is that most of the area underlying Suffolk, Essex, Herts, and Middlesex was land in Vectian time, and formed part of the large island which must then have existed in the Apto-Vectian sea. This island included the whole of Southern Belgium, with the adjoining parts of Germany and Northern France; and interesting relics of its terrestrial surface have been discovered at Bernissant and other places.

2. Intra-Cretaceous Disturbances

Recent researches have led to the conclusion that the break which is often manifest between the Lower and Upper Cretaceous series was more complete and important than had been previously supposed. It has, in fact, been shown that some terrestrial disturbances occurred between the deposition of the Wealden Beds and that of the Selbornian group, involving the production of a series of anticlines and synclines which were planed down by the waves and currents of the Selbornian sea.

In the south of England some of these disturbances have been described by Dr. A. Strahan,[1] who has shown that in Dorset they are probably of post-Vectian age. Where the Jurassic rocks

[1] See *Quart. Journ. Geol. Soc.* vol. li. p. 549.

emerge from beneath the Cretaceous strata N.E. of Weymouth Bay they display a succession of east and west flexures in which the Upper Cretaceous series does not participate. The most southerly of these is the Osmington Mills anticline, north of which is the Upton syncline, bringing in Wealden Beds; beyond this again is the Moigne anticline, also striking east and west, but partly obliterated by the post-Cretaceous Ridgeway fault.

The Broadway anticline near Weymouth appears to be a prolongation and expansion of that near Osmington, and the corresponding syncline to the north of it can be traced from Upway to Abbotsbury. At the latter place there is a fault which has a downthrow to the south of 600 or 700 feet, bringing Kimeridge Clay against Forest Marble, but this hardly disturbs the Selbornian sands, along the border of which it passes eastward. Still farther north are several other faults and folds displacing the Jurassic rocks, but passing eastward beneath the Selbornian and Chalk without affecting them in the slightest degree.

The manner in which the base of the Gault cuts across the edges of the Wealden and Vectian in the Vale of Wardour has already been mentioned. Again, south of Devizes, there are two small tracts of Vectian sand lying on Portland Beds which are crossed transversely by the base of the Gault, showing a complete unconformity between them. Farther north, in the Midland counties, the break and unconformity between the Jurassic rocks and the Upper Vectian sands is so great that the discordance between these sands and the Gault seems small in comparison, but in reality there is probably an unconformity between them.

In Sussex, again, near Lewes and Eastbourne, there is evidence of local unconformity and disturbance at or near the close of the Vectian epoch; for the mass of the Vectian is cut out, and the Gault either rests directly on the Wealden Beds or is only separated from them by some beds of coarse sand and sandy clay, which may not represent more than the basement zone of the Gault itself.

Passing now to Yorkshire, where the Lower Cretaceous series is fully represented, we find the Jurassic rocks arranged in two broad flexures, which strike east and west, and are crossed transgressively by the Upper Cretaceous series. Thus in South Yorkshire, north of South Cave, the outcrop of the Red Chalk passes successively across the Kimeridge Clay, the Corallian, the Oxford Clay, and the Oolitic Limestones till it rests on the Lias; while north of Acklam these several divisions come in again and surround the great syncline of the Vale of Pickering. It is clear that between Market Weighton and Acklam a broad anticline passes eastward under the Chalk Wolds, and was planed down before being covered by the so-called Red Chalk.

The age of this flexuring may be inferred from the relations of the Speeton Clays to the beds above and below. There is no perceptible discordance between them and the Kimeridge Clay; narrow tracts of the former occur inland, where they might be expected, on the south side of the Vale of Pickering, but the Red Chalk oversteps these and passes obliquely across the several Jurassic outcrops to Acklam, as above mentioned.

3. Upper Cretaceous Time

A. *Stratigraphical Evidence*

The successive stages into which this series has been divided were tabulated on p. 292, and the French equivalents of the English subdivisions were also indicated.

1. The Selbornian stage includes what are still generally known as the *Gault* and *Upper Greensand*, but these antiquated names merely denote different phases of one and the same set of beds, for which the name Selbornian has been proposed.[1] The clays and marls of the "Gault" are replaced by sands and sandstones more and more completely as the group is followed from east and N.E. toward the west. There is, in fact, a large area wherein the Selbornian is lithologically divisible into three parts or phases, which in descending order are :—

3. Green and grey glauconitic sands.
2. Fine sandstones (malmstone and gaize).
1. Gault marls and clays.

The Selbornian Beds attain their greatest thickness in the counties of Sussex, Surrey, Berks, Oxford, and Buckingham, being about 300 feet thick at Lewes and Eastbourne, from 250 to 300 in Surrey and East Hants, 291 at Winkfield near Windsor, and about the same at the outcrop near Didcot. In Oxfordshire the thickness is about 280 feet, and in Bucks, near Tring, it was found to be 236 feet, but N.E. of that place it becomes gradually less. We see, therefore, that the axis of greatest thickness passes from S.E. to N.W., and, roughly speaking, along a line from Eastbourne to Oxford, but the greatest thickness of the clays diverges a little to the eastward of this line, for in Bucks there is very little greensand above the "Gault."

For stratigraphical details the reader is referred to the Memoir

[1] See "Cretaceous Rocks of England," *Mem. Geol. Survey*, vol. i. p. 30.

Fig. 50.—VIEW OF HAVEN CLIFF, AXMOUTH, SHOWING KEUPER MARLS (*A*), OVERLAIN BY SELBORNIAN BEDS (*B*), CAPPED BY CHALK (*C*).

above mentioned, and to my *Handbook of Stratigraphical Geology* (Stanford). It will suffice for our present purpose to notice briefly the changes in the lithological characters of the component beds when they are traced first to the south-west and then to the north-east of the line above indicated.

The threefold division of the Selbornian is maintained to the S.W. through Berkshire and Wiltshire into North Dorset, but the Gault clays gradually diminish in thickness, partly from actual zonal thinning, and partly from replacement by sand. In Dorset the malmstone also passes into micaceous sand, and in the west of that county the whole consists of soft sands, argillaceous at the base, more siliceous above, with a bed of calcareous sandstone at the top. Near Lyme the stage is still about 200 feet thick, but by thinning out of the lower beds it diminishes to 160 near Sidmouth and to 100 in the outliers on the Haldon Hills near Exeter.

At the same time they overstep the Vectian sands and pass across the *basset* surfaces of the Jurassic strata till they rest on the Keuper Marls at Axmouth (see Fig. 50), on the Keuper Sandstones at Sidmouth, and on the Permian of the Haldon Hills. For the excellent view of Haven Cliff I am indebted to Mr. A. W. Clayden, F.G.S., of Exeter.

A special feature in this south-western development of the Selbornian sands are the layers and nodules of chert which occur in the higher part. In the formation of these, and also in that of the malmstones, siliceous sponges played a prominent part; indeed some of the beds are so crowded with the spicules and meshwork of such sponges that they are veritable "sponge-rocks," and the chalcedony of the cherts has probably been formed from a colloid solution of the silica derived from such remains.

Returning to Oxford and Bucks, and tracing the beds north-eastward, we find the malmstone and sandy beds passing first into micaceous marls, and finally into marly clays. The total thickness also gradually diminishes through Bedford, Cambridge, Suffolk, and Norfolk, till at Stoke Ferry it is only 60 feet thick, although apparently complete from base to top. Farther north it includes layers of chalky limestone and red marl, and finally it passes into the so-called "Red Chalk" of Hunstanton. This is a rough red and pink limestone, only 4 feet thick, sandy at the base, nodular in the central part, and compact near the top. Lithologically, it is a kind of chalk, but it contains the characteristic fossils of the Gault, and is a condensed calcareous representative of the Gault clays and marls. It must have been formed in an area to which the mud-bearing current did not reach, and where the débris of calcareous organisms only could accumulate, for the sand at the base is obviously derived from the underlying Vectian sands.

In Lincolnshire and South Yorkshire there is similar red rock below the Chalk, but farther north it exhibits variations. Thus, at Speeton on the coast there is 30 feet of red marl, but when traced westward this passes into a less thickness of red marly chalk, and at the N.W. corner of the Wolds there is only 18 inches of hard yellowish limestone full of quartz grains and pebbles derived from the Jurassic rocks.

Such are the deposits to be found along the surface outcrops, but the Selbornian Beds have also a broad subterranean extension under our eastern counties. Borings in these counties have shown that they everywhere underlie the Chalk, and that in most places it rests directly on the Palæozoic rocks. Further, they display similar lithological changes in passing from north to south. Thus a boring at Holkham in the north of Norfolk proved only 18 feet of red marl and blue clay between Chalk and Vectian sands. At Culford, in Suffolk, Gault clays and marls appear to be about 70 feet thick; eastward, at Stutton, only 51 feet; and in the N.E. of Essex (Harwich and Weeley) from 60 to 76 feet. Farther south, however, at Ware, it is much thicker, and glauconitic sandstones come in above the clays with a total of 206 feet. A similar development was found below Cheshunt, Loughton, London, Richmond, and Streatham (in Surrey), the thickness at these places varying from 188 to 217 feet.

In the east of Kent the Greensands disappear again, but at Chatham the Gault is still 193 feet thick. At Wye it is stated to be 185 and at Alkham (Swingfield) 164 feet, but at Dover it has diminished to 137 feet, and at Fredville, N.E. of Dover, it may be 147 feet. It is at any rate evident that it thins but slowly to the eastward, and that it may have continued either in the form of clay or sands for a considerable part of the distance between Kent and Belgium. It is possible indeed that the Gault is actually represented below Ostende, where a boring passed through the Chalk (with a glauconitic bed at its base) into what is described as "reddish chalky marl," 86½ feet thick, resting directly on Palæozoic rock.

South-east of Kent, however, the thickness of the Selbornian rapidly diminishes, for there is only 42 feet of it at Wissant; and east of the Boulonnais, borings have proved that it thins out altogether against Palæozoic rocks, but on the southern side of this land a variable set of sands and littoral deposits, known by the local name of Tourtia, was formed. By Dennebrœucq and

Pernes these are thin, but near Mons there seems to have been a deeper gulf in which glauconitic and cherty sands (Meule de Bracquegnies) were deposited to a thickness varying from 100 to 300 feet. East of Mons, however, they finally thin out against the uprising Palæozoic rocks of the Namur and Ardennes region.

Under the Paris basin there is a great thickness of Selbornian (= Albian) deposits, which are clearly a southerly continuation of our clays and greensands. Even along their outcrop on the eastern side of the basin they are lithologically similar to the English formation. Thus the "Gaize of Argonne" is a siliceous spiculiferous sandstone, like some of our malmstones, and it passes southwards into the marls of the Upper Albian. In the Departments of the Marne and Aube, the Albian has a thickness of from 350 to 400 feet, and is essentially our Gault facies; from which fact alone we might infer that the material of our Gault was carried by a current passing through that part of France.

When the Selbornian reappears on the western side of the Paris basin, it is not only much thinner but quickly passes into "Greensand." Near Havre it is still represented partly by clay and partly by gaize, with a total thickness of 36 feet, and these beds can be traced to Trouville, but seem to thin out at Villers sur Mer. Southward, in the Departments of Orne and Sarthe, its only representative is a marly glauconitic sand 10 or 12 feet thick, which is stratigraphically only a basal substratum of the overlying Cenomanian sands; moreover, no Cephalopoda have been found in it.

From these facts it is evident that the western parts of Normandy and probably the whole of Brittany were land in Selbornian time. Further, the small thickness of deposit and its gradual disappearance beneath the overlapping Cenomanian leads us to infer that very little detritus of any kind was carried into this part of the Selbornian sea from the neighbouring land.

With regard to the depth of this sea I have elsewhere [1] given reasons for thinking that its central parts ultimately became about 200 fathoms deep. The lowermost sands and clays were, of course, formed in water of less depth than that under which the fine glauconitic sands and sponge-beds of the higher zones were deposited. The Greensands are comparable to deposits now being formed off certain continental coasts in depths of from 50 to 500 fathoms, and Sir John Murray has observed that extensive growths of siliceous sponges "are most abundant in moderate depths on the 'blue muds' along continental shores, and in pelagic deposits." He gives examples of such patches of siliceous sponges in depths ranging from 100 to 530 fathoms.

[1] *Cretaceous Rocks of England*, vol. i. p. 412 *et seq.*

The Upper Gault marls of the more northern counties, from Bedfordshire to Norfolk, seem to indicate an even greater depth of water, for they bear a great resemblance to Chalk Marl, and Mr. W. Hill has shown[1] that the amount of inorganic matter, in the shape of recognisable particles of quartz, felspar, and mica, decreases as the Gault is traced northward ; while in the Norfolk marls the proposition of organic material, *i.e.* Foraminifera and fragments of shells, becomes very large. It is doubtless to this gradual elimination of transported sediment and the consequent concentration of the calcareous components that the northerly thinning out of the Gault is due.

2. **The Lower Chalk** (or *Cenomanian*) has also its typical deep-water chalky facies and its sandy littoral representatives. In England the transition from Selbornian sand or marl to the Lower Chalk is seldom an uninterrupted one ; frequently there is an abrupt change marked by an eroded surface and by the occurrence of a layer of phosphatic nodules and stones which are the siftings of previously formed beds. It is evident, in fact, that the quietude of the sea-floor on which the soft Selbornian sands and muds had been accumulated was now in many places disturbed by the action of strong currents, which washed away the finer material, and left the harder nodules and fossils to be incorporated in the basement bed of a new formation.

This bed is generally known as the Chloritic Marl. In the south of England it contains fossils derived from the *Pecten asper* zone, but in Bedford and Cambridge the derived fossils have been obtained from the Gault, and the bed is sometimes called the Cambridge Greensand.

The Cambridge Greensand has also yielded a number of rock-fragments which have evidently been brought from distant sources. These include blocks of granite, hyperite, basalt, felstone, with many varieties of sandstone, a red fine-grained micaceous sandstone being especially common ; fragments of quartzite, slate, and hornstone also occur, and one or two pieces of dark grey limestone. Some of them resemble Scotch and Norwegian rocks, but the whole assemblage could not be matched in any northern area now exposed, and their source was a mystery till Mr. Whitaker suggested that they had been derived from the area of Palæozoic rocks between England and Belgium. When he wrote in 1889 (*Guide to the Geology of London*) it was thought that the Gault might thin out against a shore-line a little beyond our eastern coasts. More recent borings have made this doubtful, but whether the shore was so near or not, it seems probable that the

[1] *Quart. Journ. Geol. Soc.* vol. xliii. p. 580 (1887).

Franco-Belgian land was the source whence these rock-fragments came.[1]

Throughout the larger portion of the area over which it extends the Lower Chalk consists of marly chalk in the lower part, and of firm grey or whitish chalk in the upper part, the two parts being generally divided by one or two beds of rather hard chalk, which is known as the "Totternhoe Stone." This facies is found from Norfolk to the Isle of Wight, and thence eastward all round the Wealden area, except that nothing exactly corresponding to the Totternhoe Stone has been found to the south of Berkshire.

The Chalk Marl is an impure chalk, containing from 55 to 80 per cent carbonate of lime, with generally a certain amount of soluble silica, sometimes in the shape of sponge spicules, sometimes in minute globular particles. The insoluble matters vary from 16 to 45 per cent, and consist partly of glauconite and partly of very fine clay or silt. This kind of chalk is analogous in structure and composition to some modern deep-sea oozes, such as those which are found in the southern part of the Gulf of Mexico. The Totternhoe Stone is a grey chalk, looking and feeling as if it were sandy, but this aspect is due to the abundance of small disintegrated shell-fragments and not to siliceous sand of any kind. Beds of a similar kind occur at other horizons in the Lower Chalk, and the shelly ingredient was probably in part derived from dead shells which lay for a long time on the sea-floor and gradually fell to pieces. Some also may have been triturated by passing through the bodies of carnivorous fish—*Ptychodus*, for instance—which were specially fitted with crushing teeth, like those of the Port Jackson shark.

The higher part of the Lower Chalk is generally greyish, but passes up into a nearly white chalk containing from 88 to 95 per cent of calcium carbonate, the siliceous particles being few and of very small size, those of quartz especially minute.

In Lincolnshire and Yorkshire the whole of the Lower Chalk is more or less hard, the proportion of clay being smaller and the amount of comminuted shell fragments larger than in the south. The total thickness is at the same time less, being only from 60 to 80, as compared with an average of 200 feet. The chalk of these northern counties has in fact the aspect of a condensed purely calcareous and deep-water formation, deposited in a part of the sea to which mud-bearing currents seldom reached, though the

[1] For a discussion of the means of transport, and the direction of the currents at this epoch, the reader is referred to *The Cretaceous Rocks of England*, vol. ii. p. 347; *Mem. Geol. Survey* (1903).

calcareous deposit was sifted and distributed by the action of a slow-moving bottom-current.

Dr. Hume has pointed out[1] that the abundance of arenaceous Foraminifera in the Chalk Marl contrasts with their rarity in the higher part of the Lower Chalk, and that the common *Textulariæ* of the former are the actual species now common in West Indian seas between 300 and 400 fathoms, while the species found in the higher beds resemble those of deeper water. Thus in passing from the lower to the higher part of this stage we seem to be tracing the effect of a subsidence which carried a large part of England through a depth of 400 fathoms of water. It is true that in the case of some kinds of animals the bathymetrical limits of genera and species may have been different from those of their modern congeners ; but Foraminifera are precisely the organisms which are least likely to have changed their habits and are consequently more to be relied upon than any other class.

Concerning the eastern subterranean extension of the Lower Chalk it need only be said that it underlies the whole of the eastern counties from Norfolk to Kent, that it recurs in Belgium and the north of France, but passes into a sandy littoral deposit in those parts where the underlying Selbornian has a similar aspect, not passing far beyond the limits of the latter.

To the above general description we need only add a brief notice of some outlying exceptional equivalents of the Lower Chalk. Thus in Devonshire, from Seaton to Sidmouth this stage is represented by a variable set of calcareous sandstones and sandy limestones from 3 to 40 feet thick ; the lowest bed being a very coarse sandstone with occasional pebbles of quartz, hornstone, and micaceous sandstone apparently derived from rocks to the west. These beds seems to represent the Chalk Marl, and are sometimes succeeded by a marly sand with *Actinocamax plenus*, but between the two there is a gap, and we must suppose that after the formation of the sandy limestones the action of strong currents prevented any further deposition of sediment till quite the close of the Cenomanian epoch.

On the opposite side of the English Channel the Cenomanian of Normandy presents another facies of the formation, which appears to be completely represented, and has a thickness near Havre of 120 feet. At the base is an equivalent of the Chloritic Marl, and the overlying beds are greyish glauconitic marls passing up into greyish-white chalk, layers of chert nodules being frequent throughout the whole set of beds, which were evidently formed in moderately deep water.

[1] *Proc. Geol. Assoc.* vol. xiii. p. 226.

These beds pass southwards inland through Calvados, Orne, and Sarthe, their main outcrop ending westward in an escarpment, which runs from the coast near Dives to and beyond the town of Vimoutiers. Near that place a long outlier of them runs out in a W.N.W. direction, and terminates in a hill 252 metres high, the base of the Cenomanian being at an elevation of about 220 metres (720 feet). This ridge points directly to Mont Pinçon, south of Aunay, where there is a small outlier of sandy marl and limestone with Cenomanian fossils at a height of about 340 metres (1115 feet). This place is about 36 miles from Vimoutiers and 23 miles south of Caen, and the ridge not only consists of Palæozoic rocks, but is part of the highest ground between Falaise and the west coast of Normandy. The outlier was explored and described by De Caumont in 1828, and though no exposure is now to be found, Professor Bigot assures me that there is no doubt of its existence or age. The importance of this small remnant of Cenomanian at so great a height is of course very great, for though there is higher ground to the southward (S. of Viré), there is nothing on the west which could have prevented the extension of similar beds across the Cotentin and the Channel Islands, and far down the area now occupied by the English Channel.

Passing now to the north-west portion of the British region, we find the Lower Chalk represented in Antrim by deposits which lithologically resemble the English Selbornian sands, and must have been formed in water of much less depth than the normal chalky facies. They consist of glauconitic sands, yellow sands with layers of chert, and calcareous sandstones. Their thickness varies considerably, but is nowhere much over 50 feet. Similar beds occur again on the west coast of Scotland in Mull and Morvern, where they are from 20 to 60 feet thick, and pass up into white sandstones of varying thickness up to 100 feet. The exact age of these latter beds is uncertain, as they contain no fossils, but include a thin seam of lignite or coal, so that they seem to be of estuarine or lacustrine origin; they may be of Middle Chalk, *i.e.* Turonian, age. Remnants of the Cenomanian sands have also been found in the islands of Skye, Scalpay, and Eigg.

At the summit of the Lower Chalk two or three layers of grey shaly marl occur throughout nearly the whole of the English area. They are found from Kent to Dorset and from Dorset to Suffolk; in Norfolk they are not conspicuous, but they recur through Lincolnshire and Yorkshire, where they are often dark-coloured and very argillaceous. In the Midland Counties they are generally in two layers, divided by a bed of white chalk, and they frequently contain rounded pellets or pebbles of such chalk. It is evident that they indicate a physical change of some importance, a change which caused the British region to be invaded by a strong and broad bottom-current, and it seems probable that this was a flow of cold water from more northern latitudes.

3. The Middle Chalk.—The succeeding beds exhibit fewer local differences than those of the Lower Chalk. In England the lower beds always consist of hard nodular chalk, some of them abounding in fragments of *Inoceramus* shells. The higher part consists of soft white chalk, composed mainly of a fine amorphous calcareous sediment, in which are scattered shells of delicate Foraminifera. The purity of this chalk, which has generally from 96 to 99 per cent of carbonate of lime, and the scarcity of fossils other than a few Brachiopods and deep-water Echinoderms, make it probable that the depth of the sea had again increased.

The Middle Chalk is thickest in the south-east (Kent and Sussex), and northward to Hertford and Cambridgeshire it is still over 200 feet, but thins to 100 feet in Norfolk. It also thins westward, but in an irregular manner, being actually thinnest in Wiltshire (80 to 90 feet) and in North Dorset, but expanding to 120 feet in South Dorset, and to about 130 feet in Devonshire. Moreover, the lower beds extend as far as Sidmouth without any notable lithological change.

In France, however, marked lithological changes are found when the Turonian is followed to the south-west. Thus near Rouen the beds which represent our Middle Chalk are about 200 feet thick, and of the usual chalky facies ; but to the S.W. the thickness decreases and the beds become marly, till in the Orne and Sarthe the lower part is a grey marl like our Chalk Marl, and the higher part consists of soft yellowish sandy stone (tuffeau), the whole being seldom more than 60 feet thick.

Again, on the other side of France, where the Turonian emerges from beneath the eastern part of the Paris basin, it also assumes a "chalk-marl" facies. In this form it extends northward under the western part of Belgium and eastward to the Ardennes. The lower beds, known as *diéves*, are soft bluish-grey argillaceous marls, the higher consist of alternating beds of similar grey marl and hard compact chalk (*fortes toises*). These beds in Belgium thin out eastward and are overlapped by higher zones.

Thus we see that both eastward and westward the Turonian chalk of France passes into beds which are lithologically similar to the Lower Chalk of England, and there can be no doubt that in each case this was in the direction of land. From these facts several inferences may be drawn : in the first place, it is clear that the pure chalk facies of Northern France, Southern and Eastern England, is a deep-water facies of the formation. Secondly, it can hardly be doubted that the English Middle Chalk in passing westward toward Wales passed into a marly facies, and perhaps finally into a sandy one. Lastly, the fact that the Devonshire chalk does not show much lithological change must be taken as evidence that the shore of the Turonian sea lay much farther westward in England than it did in Northern France. It is true that the Beer Stone is a rough shelly limestone, composed almost entirely of fragments of Inoceramus shells and Echinoderm plates; but the amount of terrigenous matter is small (1·8 to 3·5 per cent), and the deposit is one that might have formed a local shell-bank in the track of a current, and in fairly deep water.

We must now briefly refer to the remarkable absence of any definite marine representative of the Middle Chalk in Ireland and Scotland. In Antrim the highest Cenomanian sandstone is overlain unconformably by other sandstones which have yielded Upper Chalk fossils. It is true that certain beds have been doubtfully assigned to the Middle Chalk by Dr. Hume, but he did not obtain any characteristic Turonian species from them, and in any case their thickness is very small.

On the west ocast of Scotland, unless the white sandstones mentioned on p. 317 are of this age, there is nothing to represent the Middle Chalk. It is evident that in this part of the British region there was nothing like the continuous subsidence which we have traced in the eastern and southern areas.

4. The Upper Chalk.—Throughout the greater part of England the Middle Chalk is surmounted by beds of hard nodular chalk, or by several beds of hard compact limestone containing layers of green-coated calcareo-phosphatic nodules. This latter facies is known as the "Chalk Rock," and is typically developed in the counties of Wiltshire, Berkshire, and Oxfordshire, but the base of the zone of *Holaster planus* can be traced throughout Southern England and Northern France. The Chalk Rock often contains glauconite and sometimes even visible grains of quartz; it is often rich in fossils, which include Gasteropoda of the same genera, and sometimes of the same species, as occur in the Lower Chalk.

This sudden recurrence of peculiarities that characterise the Chalk Marl and Totternhoe Stone, associated with a similar fauna, compels us to conclude that previous conditions had been restored by the rise of a large portion of the sea-floor, so that the water became less deep. The beds of Chalk Rock are often sharply marked off from one another, each having a layer of nodules at its base, as if they had been sifted out of their original embedment by the action of a current. Such, no doubt, was really their mode of accumulation ; they were formed by chemical action in soft calcareous ooze, which was liable to be sifted and swept away from time to time by the action of bottom currents. Similar hard floors and hard nodules have been found at great depths in modern seas.

Above the zone of *Hol. planus* comes the great mass of the Upper Chalk, which includes the Santonian and Senonian of French geologists. Some parts of this consist of firm and compact chalk, and other parts of soft white brittle chalk ; some parts again include frequent and regular layers of flints, and in other parts flints are scarce. The Upper Chalk has been divided into several zones, and the highest one of which any considerable extent now remains in England is that characterised by *Belemnitella mucronata*, which has been traced from Kent to Dorset and from Dorset to Norfolk. There is a still higher zone, that of *Ostrea lunata*, but it has only been found near Trimingham and Mundesley in Norfolk.

The Upper Chalk is therefore most complete in Norfolk, where its thickness is probably about 1150 feet. In the Isle of Wight some of the zones are thicker than in Norfolk, with the result that though the highest part is wanting, there is still about 1240 feet of Upper Chalk in that island, and its original thickness may have been 1400 feet or more. It appears to have been equally thick in Dorset, where again its upper surface is one of abrupt erosion.

In the north of France and under the basin of Paris there is a similar great thickness of Upper Chalk, but when the beds are traced to the southward and south-westward they become less purely calcareous ; the introduction of fine micaceous sand making it evident that both in Central and Western France there was still some land from which the finer and lighter débris of granitic and gneissic rocks was carried into the neighbouring waters.

The microscopic studies of Professor Cayeux have shown that in the Department of the Eure there is a gradual transition from the pelagic white chalk, with its minute Foraminifera, to the yellowish sandy limestones and siliceous chalks of Touraine, the lower beds of the Touraine series being crowded with Bryozoa and large Foraminifera, and the higher chalky beds being full of the remains of siliceous sponges.

M. de Grossouvre has proved that the zone of *Marsupites* is represented in Touraine by that of *Spondylus truncatus*, and has thus established a means of comparing the chalk of the typical northern areas with the local succession of Villedieu and Châteaudun. It is thus seen that the beds which represent the zones of *Holaster* *planus*, *Micraster cortestudinarium*, and *M. coranguinum* are calcareous sandstones, sandy limestones, and glauconitic marls, with a total thickness of about 50 feet near Villedieu. The zone of *Spondylus truncatus* is a nodular siliceous limestone, and it is succeeded by siliceous chalks with sponge-remains, these beds being evidently formed in much deeper water than the underlying sandy micaceous and glauconitic deposits. In France, therefore, as in England, we have clear evidence of an uplift at the close of Turonian time, followed by renewed subsidence.

There is every reason to suppose that the Senonian chalks spread westward across the whole of Normandy, but no remnants of them now remain to the west of Cape Antifer on the coast, or farther west inland than Bouloire near Le Mans. The only deposit of late Cretaceous age in Western Normandy is the Baculite limestone of Valognes. This consists of alternating hard and soft beds of yellowish rock, constructed entirely of organic remains—the shells of Mollusca, Brachiopoda, and Foraminifera, with many fragments of Polyzoa and small corals. Some of the beds are loose, and not unlike our Coralline Crag, so that it might have been formed in water of 40 or 50 fathoms. Its fossils prove it to be of the same age as the brown chalk of Ciply in Belgium, and of the Kunraed limestone of Limbourg, which belong to the close of the Senonian epoch. It rests partly on Cenomanian sandstone and partly on Palæozoic rocks, so that if any Turonian and other Senonian chalks were deposited on the Cenomanian of the Cotentin, they must all have been destroyed during the gradual uplift of the sea-floor before the time when the Baculite limestone was formed.

There is some evidence that they did exist, for pebbles of hard chalk have recently been discovered in the floor of the English Channel between Cornwall and Brittany at depths of 40 to 50 fathoms. These stones have been described by Mr. R. H. Worth, who thought that some of them were comparable to Melbourn Rock; but having been favoured by him with the opportunity of examining the sections cut from these chalks, I incline to regard them as pieces of indurated Middle Chalk, while one at least has a strong resemblance to Chalk Rock.

Moreover, many pieces of Chalk and flint, with other rock-fragments, have lately been dredged off the west coast of Ireland in depths of from 100 to 500 fathoms. They are most abundant off the coast of Kerry, and have been briefly described by Messrs. Cole and Crook.[1] Some of the chalk stones are hard, angular, and greyish-

[1] "On Rock-Specimens dredged from the Floor of the Atlantic," *Mem. Geol. Surv. Ireland* (1910).

brown in colour, others are soft and white, and two pieces are glauconitic, but no comparison with English Chalks has yet been made. The authors say that "the whole assemblage of stones, if we omit the sandstone, is not at all what one would expect as the result of glacial deposition from the nearest existing land." They conclude that the stones are more or less *in situ*, and that those of Cretaceous age are the remnants of an outlier of such rocks near the place where they occur.

If this inference is correct, we must believe that very little of the western land remained above water during the formation of the higher Senonian Chalk, and that there was free communication between the Atlantic and European seas.

We must next briefly consider the deposits which represent the Upper Chalk in the north of Ireland and the traces which remain in Scotland. In Antrim, above the break and unconformity mentioned on p. 319, the succession where best developed is as follows:—

	Feet.
3. White limestone with *Bel. mucronata*	100
2. Hard pinkish glauconitic limestone, with quartz-grains and phosphatic nodules	4
1. Glauconitic limestones passing down into glauconitic sand .	16

The age of No. 1 of this series is somewhat doubtful, but it appears to be newer than the zone of *Holaster planus*, while No. 2 may be a condensed representative of the *M. coranguinum* zone. The white limestone has a band containing *Marsupites* plates at its base, so that its horizon is known, and the 20 feet below must consequently represent parts of a thickness of some 400 feet of chalk in Sussex and the Isle of Wight.

In Scotland there is still less to represent the Upper Chalk. The white sandstones of the west coast (see p. 317) are overlain by a few feet of argillaceous greensand passing up into glauconitic limestone, the two being only 5 to 7 feet thick, and apparently the equivalents of the similar basement beds in Antrim. Above these is a bed of white *Bel. mucronata* chalk, from 3 to 10 feet thick, which is evidently a mere remnant of a much thicker deposit, for in some places it is overlain by Eocene marls, at the base of which there is a bed of weathered flints a foot in thickness.

In the N.E. of Scotland evidence has recently been obtained that a very different set of Cretaceous deposits once existed on that side of the country. The glauconitic sandstone of late Vectian age was mentioned on p. 300, and it has since been found that the Drift of Aberdeenshire also contains lumps of chalk; other pebbles of chalk have also been dredged from the deeper parts of the Moray Firth. Specimens of all these are now in the hands of Mr. W. Hill, and the results of his examination will doubtless be published in due course. Meantime he kindly permits me to state some of the ascertained facts :—

The specimens seem to have been derived from a succession of chalky deposits which contained proportions of terrigenous matter varying from 10 to 1 per cent, the amount presumably diminishing from below upward. They all contain free and often well-preserved tests of Radiolaria, with sponge spicules and much colloid silica, thus differing very considerably from any kind of English chalk, but resembling some Swedish and Danish chalks. Presumably some of the beds belonged to the Upper Chalk, as many flints also occur in the Glacial Drift, and have yielded a certain number of fossils, which include the following well-known Senonian species :—

Echinocorys scutatus.	Belemnitella mucronata.
Cidaris sceptifera.	Pecten cretosus.
Galerites conicus.	Terebratula carnea.

With regard to the general physical and bathymetrical conditions under which the central mass of the English Upper Chalk was accumulated, the reader is referred to the Memoir on the "Upper Chalk of England," written by Mr. W. Hill and myself, and published by the Geological Survey (1904). To complete the present review, however, I will here give a brief summary of the conclusions arrived at in that volume.

Our belief is that, after the uplift which produced the episode of the Chalk Rock, subsidence again set in and continued steadily for a long time, reaching its greatest extent while the chalks of the *Marsupites* and *Actinocamax quadratus* zones were being formed. These chalks are the finest and purest of the whole Cretaceous series; the amount of terrigenous matter which they contain is generally less than 1·3 per cent of the whole mass, and it consists of the very finest dust, such as might easily be distributed by wind. It is only in Yorkshire that the quantity sometimes reaches over 3 per cent, but though larger in quantity the particles composing it are not larger in size. Apparently Yorkshire was nearer to the source from which the dust was carried by prevalent winds.

From the deep submergence of the Anglo-Parisian area, which must have made it an integral portion of the adjoining Cretaceous ocean, there was a gradual recovery and re-elevation. The effects of this reverse movement are distinctly visible in the chalk of the highest zone as developed in Norfolk. Under the microscope this is seen to be a more shelly kind of chalk than that of the underlying zone, and to include minute grains of glauconite. After treatment with acid there is a residue of from 2 to 3 per cent of siliceous matter, more than half of which is fine quartz sand. The fauna of this chalk is also remarkable, and recalls that of the Chalk Rock and zone of *Holaster planus*, for it includes species of Cerithium, Turbo, Arca, Nucula, etc., which do not occur in the intervening mass of chalk. There are also a large number and variety of Bryozoa.

Here the British record ends; but if we cross the North Sea we find in Denmark and at Rugen, on the north coast of Prussia, chalky limestones which seem to continue the succession, and have the aspect of comparatively shallow-water deposits.

In conclusion, and in order that the reader may clearly realise the successive movements in which the British region appears to have participated during the deposition of the Upper Cretaceous series, these have been expressed in the form of a diagram (Fig. 52) to show the supposed fall and rise of the sea-floor through successive bathymetrical levels.

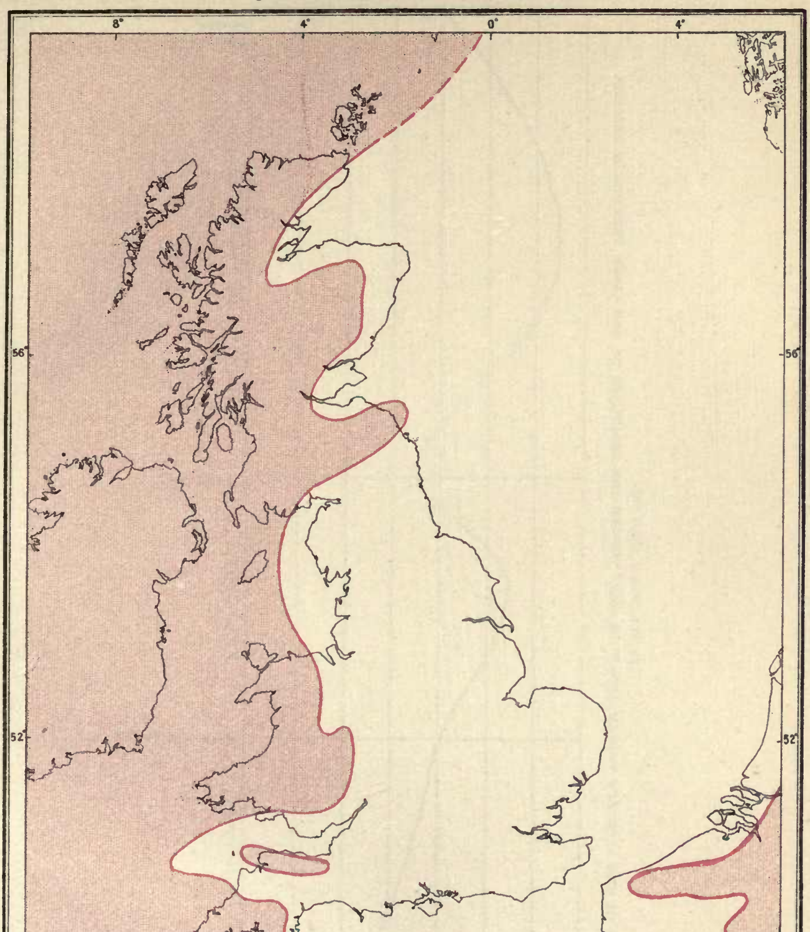
It must be understood, however, that this is only a diagram of the probable relative proportions of the movements, and it must not be taken to express a belief that the maximum amount of subsidence was exactly 700 fathoms. It may have been more, and it may have been less; the line is only drawn to that level to indicate roughly the probable extent of the depression in Senonian time as compared with that of the Turonian epoch.

B. *Physical History and Geography*

The disturbances which took place during or after the deposition of the Vectian sands, as recorded on p. 308, were followed by a great and prolonged period of subsidence, which continued until the greater part of France and England, and perhaps of all the British Isles, were submerged beneath the Cretaceous sea.

Considering the depth of Gault clay which overlies the eastern Palæozoic area, and the manner in which the Gault and Upper Greensand overstep the members of the Jurassic system westward, it is evident that the eastern part of the British region subsided much more rapidly than the western, so that the Jurassic strata were bent down, as it were, beneath the advancing Cretaceous sediments. The waves of the Cretaceous sea cut obliquely across the older strata, forming a plane of marine denudation which was carried rapidly westward, and had a gentle slope or inclination eastward.

Fig. 51.—GEOGRAPHY OF SELBORNIAN TIME.



London: Edward Stanford, 12, 13 & 14, Long Acre, W.C.

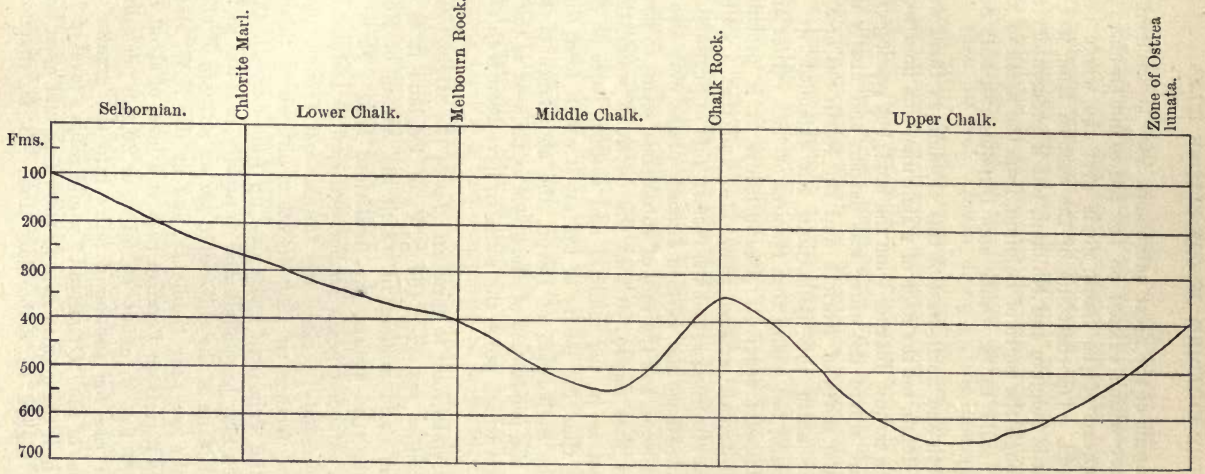


Fig. 52.—DIAGRAM OF THE PROBABLE BATHYMETRICAL CHANGES DURING THE DEPOSITION OF THE UPPER CRETACEOUS DEPOSITS IN SOUTHERN ENGLAND.

The first result of the great subsidence was the submergence of the promontory which existed on the site of our eastern counties, and the outspread of the Gault muds over the whole of south-eastern England. The coast-line of the eastern land was carried far back towards Belgium and Holland, but a promontory running westward through the south of Belgium, from the north of Mons by Tournai and Lille to St. Omer and Dunquerque, still remained above sea-level.

To the north and north-west of this promontory there was a sea of increasing depth, on the floor of which fine blue mud was being deposited for a certain distance from the land, but passing gradually into grey marl where the water was deeper, and finally into red marl below the north of Norfolk and the North Sea area. How much farther north this Selbornian sea extended we do not know for certain, but seeing that remains of both earlier and later Cretaceous deposits occur in Aberdeenshire, it is probable that Selbornian sediments existed there also, and that a gulf of the Cretaceous sea stretched round the eastern side of Scotland.

By this subsidence the western Jurassic plains were also carried below the sea-level, but the rate of subsidence seems to have been less rapid in that region, so that the depth of water there was never so great as in the midland and eastern parts of England. At the same time the purity of the sands which form the upper portion of the Selbornian of Devon, the abundance of siliceous sponges, and the persistence of chert-beds as far west as the Haldon Hills, are facts which prove the water to have been both clear and fairly deep.

When we endeavour to form an idea of the original extension of the Selbornian sea over the S.W. of England it is well to remember the rapid manner in which the Albian of Normandy thins out westward against the Armorican land. It is evident that the sea extended much farther westward in Devonshire than it did in Normandy, because the Jurassic and Triassic plains had also extended farther in that direction, but where these plains ended and the Palæozoic rocks rose up from beneath them, the Cretaceous sea may have shallowed as rapidly as it did in France.

The basal plane of the Selbornian has an altitude of about 400 feet above the sea near Sidmouth, and at the N.W. end of the Haldon Hills it rests on Permian rock at a level of about 700 feet, a rise of 300 feet in about 15 miles, or 20 feet per mile. Prolonging this rise for another 4 miles into the granite of Dartmoor, the base of the "Greensand" would reach a level of 780 feet, where even now the granite rises to 1000 feet, and must have been very much higher in Selbornian time. It is, therefore, very unlikely that Dartmoor, parts of which are still nearly 2000 feet above sea-level, was submerged by the Selbornian sea.

We can check this estimate by noting the westward rise along the northern ridge of the Blackdown Hills. We find that there the base-line, as drawn on the recently published Geological Survey map, undulates so much that the total rise between Castle Plain and the western end of the ridge (a distance of 9½ miles) is not more than 50 feet. Again, along a little more southerly line to Hackpen Hill, the rise is only about 30 feet in 9 miles. If these undulations were continued westward, and the average rise was not more than 5 feet per mile, a prolongation for 8 miles would only bring the base of the Selbornian to a height of 790 feet on the Carboniferous area south of Bampton, where the ground is now about that very height above the sea. As a matter of fact it is probable that the actual rise in Central Devon was greater, and that the Selbornian sands passed completely across the county between Dartmoor and Exmoor ; but the facts above mentioned tend to prove that the rise of 20 feet per mile between Sidmouth and the Haldon Hills is a maximum amount, and that neither Dartmoor nor Exmoor was submerged by the Selbornian sea. This conclusion finds confirmation in the complete absence of cherts in the surface soil of those areas.

We can hardly doubt that the Selbornian sea swept completely across the central parts of Somerset north of the Blackdown Hills as far as the Mendips, and also westward over the area of the Bristol Channel. East of Bruton, on the borders of Wiltshire and Somerset, there is a bold escarpment of Selbornian sand and Gault resting on Oxford Clay at a level of about 600 feet. The Mendip Hills may possibly have been an island for a time, but they were probably soon submerged, either in Selbornian time or early in the succeeding Cenomanian epoch.

We may therefore suppose that between Dartmoor and South Wales a broad bay or gulf of the Selbornian sea extended westward beyond the present confines of Devon, Exmoor, and the Quantock Hills, forming islands near the mouth of this bay. How far westward the bay extended there is nothing to base an opinion upon, but at the same time there is no reason to suppose that it was more than a bay in the western land.

In considering the farther course of the coast-line toward the north, and the probable extension of the Selbornian sea across the central parts of England, this is very little to guide us except the analogy of its transgression across the Jurassic series, both in Devonshire and in Wiltshire. We may safely assume that the sea gradually ate its way westward through and across the Jurassic as the area gradually subsided. We may take it also that the deflexion of these strata eastward beneath the Gault means that the vertical extent of the subsidence was greatest in the east, and became less and less toward the west, so that it was some time before the movement reached the borders of Wales.

It is, however, very difficult to form an idea how far the sea was carried westward by the close of Selbornian time, because we do not know for certain the date of the movements which produced the flexures of the Midland Counties and the final arching of the Pennine chain. In the Midlands there are four great anticlines, with intervening and corresponding synclines, and, as Professor Lapworth has pointed out, they are not parallel to one another, but seem to radiate from the southern end of the Pennine range. The anticlines are: (1) that of the Wrekin, which strikes S.W. and N.E. toward the North Staffordshire coalfield ; (2) that of the South Staffordshire coalfield, which strikes S.S.W. ; (3) that of the Warwickshire coalfield, which runs a little east of south ; and (4) the Leicestershire coalfield, the boundaries of which strike S.E.

All these flexures seem to be of the same age, and as they all involve Carboniferous, Permian, and Triassic rocks they are evidently post-Triassic ; further, from the position of the Lias outlier in Cheshire, outside the boundary faults of the western anticline, we may infer that they are post-Liassic. As I have argued on p. 244, being post-Liassic means that they are post-Jurassic. Again, there is no ground for supposing them or the Pennine arch to be of Purbeck-Wealden date, nor is there anything to connect them with the later intra-Cretaceous flexures which strike east and west. Consequently they appear to be post-Cretaceous, and either of Eocene or Miocene age.

The same chain of reasoning will also apply to the Pennine chain, in respect of the date of the final movement which completed the uplift as we now see it, and produced the continuous broad geanticline of the whole range from Derby to Northumberland with the synclines which flank it on the east and on the west. Note also should be taken of the Lias outlier in the Carlisle basin.

On this point I am pleased to find myself in accord with my friend, Dr. J. E. Marr, who has taken the same view of the age of the Pennine anticlinal when considering that of the dome of the Lake District. He remarks that "the arguments previously advanced in the case of the Rhætic [and Lias] strata on opposite sides of the Pennines apply also to the Chalk, which probably occupies part of the Irish Sea."[1]

Still, we are not out of our difficulties in trying to fix the

[1] *Pres. Address Geol. Soc.* vol. lxii. (1906), p. lxxxvii.

position of the western coast-line of the Selbornian sea, for under the conditions above indicated the shore may have lain anywhere between a line connecting Warwick and Derby, and a more western line through the central parts of Hereford and Shropshire. Again, farther north, it may have lain over the line of the Pennine range or out in the middle of the Irish Sea.

So far as I can see, there are only four considerations which have any bearing on this question: (1) the analogy of the transgression of the Selbornian in the south of England; (2) the calcareous nature and small thickness of the Red Chalk in Yorkshire; (3) the absence of any representative of the stage in Ireland; (4) the purity of the Lower Chalk in Lincolnshire and Yorkshire.

The first of these facts suggests that there was a similar overstep in the Midlands, and that the higher Selbornian sands were carried as far west as the Palæozoic areas of Hereford and Shropshire. The second suggests deposition at a considerable distance from a shore, the remarkable attenuation of the deposit being probably due to the existence of a submarine bank, the result of the intra-Cretaceous ridging up of the sea-floor. The third proves that the sea did not reach as far west as Antrim until the succeeding Cenomanian epoch.

The fourth confirms the second, for it is not likely that either the Selbornian or Cenomanian stages would be represented by such purely calcareous deposits if a tract of land lay within 30 or 40 miles to the westward, and broadened out into a still larger area toward the north.

It is, therefore, most probable that the western shore-line ran northward along the Welsh border and through Denbighshire, thence to the Isle of Man, and then north-eastward along the Scottish border to the North Sea. These are the geographical conditions which I have ventured to delineate on Fig. 53, and there are only two portions of the coast-line there shown which remain to be justified.

I have not taken the Selbornian Sea over Cornwall, for at the time we are dealing with the Cornish highlands probably rose to as great a relative height above sea-level as Dartmoor did, the present southerly declination in the height of the granite areas from Dartmoor to Land's End being probably the result of unequal subsidence in Tertiary time.

With regard to the east of Scotland, we know that glauconitic sandstone of Vectian age existed there, and it is probable that this was succeeded by some Selbornian deposit, though no actual remains of such a deposit have yet been found. Recently, however, chalks of various kinds have been found in the glacial deposits of Aberdeen (see p. 322), and their occurrence increases the probability that a gulf of the Cretaceous sea was already established between Scotland and Norway, reaching to, and probably beyond, Caithness.

Having thus fully discussed the physical conditions under which the Selbornian deposits were formed, and having reached certain conclusions with regard to the extension of the Cretaceous sea over the British area at that time, the subsequent changes in physical geography can be more briefly indicated.

The evidence adduced on pp. 313 and 317 suffices to prove that the Cenomanian sea covered a wider area than the Selbornian. This is especially clear in the west of France, in the N.E. of Ireland, and in Scotland. The presence of sandy equivalents of our Lower Chalk in all these districts proves that much more of the western land was submerged in Cenomanian time, and that the sea had again occupied the area of the great north-west gulf which had been such a conspicuous feature in the geography of the Triassic and Jurassic periods.

It is difficult to say how far west the sea was carried by this subsidence, or to what extent Ireland and Scotland were submerged by the further subsidence of Turonian time. We cannot judge of the levels reached by the Cretaceous sea from the present relative level of the Cretaceous strata in Antrim and Mull, because these areas underwent great local depression in Tertiary times, after the outpouring of the mighty lava-streams under which the Mesozoic strata are buried. We may be sure that in pre-Tertiary times the relative level of these districts was many hundred feet higher than that at which they now lie, while the height (over 1000 feet) attained by the base of the Greensand in Morvern (Argyleshire) shows that the Cretaceous sea must have covered considerable areas in Western Scotland, and makes it probable that all the lowland district was submerged so as to form a strait or channel between the Highlands and the southern uplands. The latter, with the Cheviot Hills and the higher parts of Cumberland, Westmoreland, and Yorkshire, must have formed a group of islands; and it is not unlikely that the northern part of Ireland presented a similar appearance, glauconitic deposits like those of Antrim being deposited in the comparatively shallow waters which lay between the islands of an archipelago.

A few words may here be said about the climate of this epoch, for that of Northern Europe appears in Upper Cretaceous time to have been much milder than it is at the present day. The assemblage of plants found in the Upper Cretaceous deposits of

Central Europe, N.W. America and Greenland, includes not only Ferns, Cycads, and Conifers, but many dicotyledonous plants belonging to genera which now live in temperate and subtropical climates, as, for instance, *Magnolia*, *Myrtus*, *Myrica*, *Ficus*, *Andromeda*, *Sassifras*, and *Credneria*.

Dr. A. R. Wallace has pointed out that the explanation of this extension of an abundant temperate flora into northern regions is probably to be found in the very different distribution of land and sea which then prevailed. At the present time very small parts of the warm equatorial currents find their way into regions within the Arctic Circle, the only one which exercises much effect being the Gulf Stream. "But if there were other and wider openings into the Arctic Ocean, a vast quantity of the heated water which is now turned backward would enter it, and would produce an amelioration of the climate of which we can hardly form a conception."[1]

Moreover, if this was accomplished by a subsidence and a consequent lowering of the height of land within the Arctic and Temperate regions, the conditions would not favour the accumulation of ice and the *winter* temperature of the whole region would be raised, and it is the severity of the winters which limits the northerly range of many plants and trees.

There is geological evidence that in Cretaceous and Eocene times more complete communication existed between tropical and northern seas than is the case at the present day. The great east and west ranges which now traverse Europe, Asia, and North Africa were not then in existence, or only formed groups of islands in an extensive ocean which spread over large parts of these continents. From this equatorial ocean it is probable that there were several openings northward, one being through the Greenland Sea and another across Asia; through these warm currents would pass into the Arctic seas, warming the air and ameliorating the climates of the islands and continents between which they flowed.

Whatever may have been the extent to which the British region was submerged in Cenomanian time, it is certain that it must have sunk still farther beneath the sea during the formation of the Middle Chalk. At the same time we must remember that, though the vertical depth of the water was greater, the superficial extent of the sea may have been only slightly increased. It is probable indeed that all the lower lands consisting of Jurassic strata had been covered by the sea of Cenomanian time, and if the slopes above these lowlands were generally steep, the Turonian subsidence would not have increased the actual area of the sea to anything like

[1] *Island Life*, 2nd Edition, p. 190.

the same extent; in fact the actual geographical change produced by the further subsidence may have been small, but it would have an important physical influence in abating all processes of subaerial erosion and consequently in diminishing the amount of terrigenous material carried down by the dwindling streams into the sea.

We have seen that though it is very doubtful whether any deposits of Middle Chalk age now exist in Ireland or in Scotland, yet it is not only possible but probable that such deposits did once exist, and presumably they were chalky deposits formed in deeper water than the glauconitic sands of the Cenomanian. Their absence is probably due to their destruction during the subsequent elevation of the area.

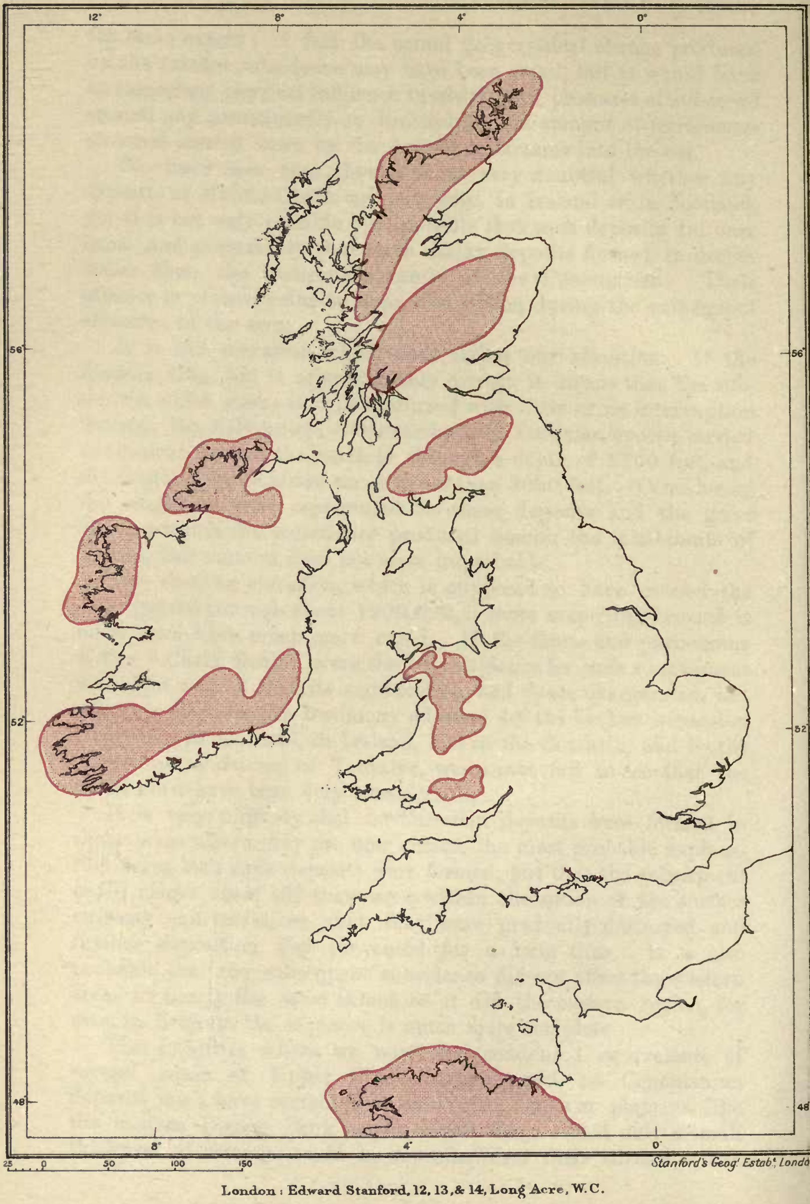
It is this elevation which next claims our attention. If the diagram (Fig. 52) is approximately correct, it means that the subsidence which seems to have continued with little or no interruption through the Selbornian, Cenomanian, and Turonian epochs carried the central part of the sea-floor through a depth of 2700 feet, and the depth of water above was not less than 3000 feet. Considering the length of time represented by these deposits and the great changes which the subsidence produced among the inhabitants of the sea, this amount does not seem improbable.

The ensuing elevation, which is supposed to have carried the floor upward through about 1200 feet, is more surprising because it must have been much more rapid. If the fauna and phenomena of the "Chalk Rock" were the only evidence for such a movement we might suspect that its signification had been exaggerated, but when we consider the testimony afforded by the broken succession of deposits in Scotland, in Ireland, and in the Cotentin, and by the calcareous sandstones of Touraine, we cannot fail to see that the uplift must have been very considerable.

It is very unlikely that no Turonian deposits were formed in those areas where they are now absent, the most probable explanation being that such deposits were formed, but that the subsequent uplift raised them till they came within the action of the surface currents and waves, so that they were gradually destroyed and further deposition was prevented for a long time. It is also probable that the subsequent subsidence did not affect the western areas to nearly the same extent as it did the eastern region, for even in Belgium the sequence is much more complete.

The localities where we now find condensed equivalents of several zones of Upper Chalk superimposed on Cenomanian deposits must have remained as submarine banks or plateaus, like the modern Dogger Bank in the North Sea, so that only a small thickness of material could be deposited over their surface. The

Fig. 53.—GEOGRAPHY OF LATE SENONIAN TIME.



London: Edward Stanford, 12, 13, & 14, Long Acre, W.C.

case seems analogous to that of the thin bed of red and yellow limestone in Yorkshire, which is the condensed equivalent of the whole of the Selbornian clays, marls, and sands of Southern England.

It was not until the zonal epoch marked by the presence of the curious Crinoid known as *Marsupites* that the western areas participated in the renewed subsidence to any great extent. This is clearly shown in Antrim, and though the fossil has not yet been found in Scotland, its occurrence may be anticipated at the base of the white chalk on the western coast.

We now have to consider the general effects of this subsidence, and especially to what extent it modified the western region. If the views above expressed are correct, it is evident that in the north-west area the subsidence started practically from sea-level and progressed much more slowly than it did over the English area; consequently the depth of the water never became so great, and the Senonian subsidence may not have submerged Scotland and the north of Ireland to any greater extent than the Turonian subsidence had done.

So far as we can judge, this seems also to have been the case in Western France; but it was not the case in the south-west of England, for in Devon the chalky series is quite complete from the Turonian to the zone of *Micraster cortestudinarium*, and there is clear evidence from *remanié* flints that this zone was succeeded by those of *M. coranguinum* and of *Marsupites*. Presumably these were followed by the still higher zones which are fully developed in Dorset. Since all these are deep-water chalks, it seems nearly certain that the Senonian sea must at one time have covered even the highest parts of Dartmoor, and consequently the whole of Devon and Cornwall, with much of the land which then lay to the westward.

Again, from the quantity of chalk-stones and flints dredged off the coast of Kerry and Donegal, it seems probable that the Upper Chalk extended continuously out into the Atlantic and round the west of Ireland. Indeed the recent discoveries of chalk pebbles on the sea-floor outside Ireland and Scotland, as well as near the mouth of the English Channel, oblige us to reconsider former conceptions of the geographical conditions under which the highest Chalk was accumulated. We are compelled to conclude that little except the highest parts of the British region remained above water when the chalk of the *B. mucronata* zone was formed. The region must have been reduced to an archipelago of islands, and I have ventured to indicate the probable position of these islands in Fig. 53, allowing as far as possible for subsequent coast-erosion and successive alterations of level in Tertiary times.

It thus becomes a question whether the whole of Wales was submerged beneath the sea of the Upper Chalk. This, of course, is very different from asking whether the Upper Chalk (as chalk) spread over the whole of Wales; for chalk is unquestionably a deep-water deposit, and if any deposits of the same age were ever formed over Wales, they would have been either glauconitic sands and marls or fine pulverulent calcareous sands and siliceous limestones (gaizes and malmstones). The question is whether the subsidence in the west was sufficient to carry the sea-surface over the whole or only the greater part of the Welsh area.

There are two lines of evidence which bear on this question: (1) the probable complete submergence of Dartmoor and Exmoor between the same lines of longitude; (2) the fact, long ago observed by Ramsay, that the relative heights of the mountains of South Wales are such that none rise above levels which would be touched by a plane slightly inclined from north to south.

Seeing that Exmoor rises to 1700 and Dartmoor to 2000 feet, it is not assuming too much to suppose that all the parts of Southern Wales which are not more than 2000 feet above the sea were submerged at the same time as Devonshire. This would leave nothing above water save the Brecknock Beacons, the Black Mountains (on the Brecknock and Hereford border), with Plynlimmon and a few other smaller mountains. Of course the pre-Cretaceous contours of the country were very different from those which it now exhibits; all heights have been greatly reduced by the work of subaerial agencies during Tertiary times, and so also has the height of Dartmoor. But assuming that those parts of Wales which are now less than 2000 feet above sea-level were submerged at the same time as Dartmoor, then South and Central Wales would have been reduced to a small archipelago of islands. In North Wales there may have been a larger island extending from Carnarvonshire to Cader Idris in Merioneth, and to the Berwyn Hills on the east, all these areas being even now well over 2000 feet.

As regards the other line of evidence, Ramsay's view was that the whole of South Wales had been completely submerged at some period (date uncertain), and that its more ancient surface had been reduced to a "plain of marine denudation" by the erosive action of sea-waves, first during the subsidence, and, secondly, during the time of its gradual emergence. I am aware that Professor Davis is of opinion that such a plain or peneplain can also be formed by the long-continued action of subaerial agencies, but I do not think he has conclusively demonstrated the truth of his theory in this or any other British case.

Consequently, I believe that Ramsay's theory of a marine planation of Wales is a more probable explanation of the facts than the other one. If it is the correct explanation the most probable period for the production of such a plane was the subsidence of later Cretaceous time, and the subsequent resurgence at the dawn of Eocene time. I accept it, therefore, as confirmation of the view that Wales, or at any rate the greater part of that principality, was submerged beneath the Cretaceous sea. Dr. A. Strahan is of the same opinion, and has expressed it in an able discussion of the "Origin of the River System of South Wales" (see *Quart. Journ. Geol. Soc.* vol. lviii. p. 207).

Since this was written Mr. W. G. Fearnsides has published the statement that in Central Wales there are evident remains of a peneplain "standing at about 2000 feet above sea-level in the neighbourhood of Cader Idris, and sloping gently away to the south-east across Merioneth and Cardiganshire."[1]

Again he writes: "Within the Snowdonian mountain district the bigger hills often stand up above the level of the peneplain, but gashed by later glaciation, they often show a well-marked shoulder independent of structure at a level corresponding to the peneplain."

Mr. Fearnsides does not venture to refer the peneplain to any particular period, and though he admits it may be one of marine erosion, he inclines to the view that it is "an early Tertiary surface of subaerial denudation." Seeing that the level at which it occurs is exactly that at which I have estimated the Cretaceous sea is likely to have reached, I regard its existence as a confirmation of the opinion above expressed.

[1] "Geology in the Field," *Geol. Assoc.*, Jubilee Vol., 1910, p. 820.

CHAPTER XII

THE OLDER TERTIARY OR PALÆOGENE PERIOD

THE great subsidence of the European region during the Cretaceous period was eventually succeeded by a reverse movement which gradually lessened the depth of water and brought up parts of the Cretaceous sea-floor to and above the surface of the sea. The British region was one of the areas so elevated, and consequently we find that between the Chalk and the overlying Eocene deposits there is a decided break and discordance. This is marked not only by a certain amount of unconformity, but by the great contrast between the two kinds of deposit, the chalk being a pure deep-water limestone and the lowest British Eocene a fine sand formed in a shallow sea. The contrast between the faunas of the two deposits is still more remarkable, for it is much greater than that between faunas of the Upper and Lower Cretaceous series.

From the time of this post-Cretaceous elevation down to the present day the greater part of the British region has been a terrestrial surface, and until late in Pleistocene time it was always more or less connected with the European continent. The history of our region therefore during Tertiary times resolves itself into two parts: (1) the history of the areas which were from time to time submerged beneath the seas and estuaries; (2) the history of the land-surface and the gradual evolution of its present physical features.

This chapter will be devoted to a consideration of the areas in which Eocene and Oligocene sediments were deposited, leaving the terrestrial phenomena of the same Palæogene period to be dealt with in the next chapter.

1. EOCENE TIME

The Older Tertiaries of North-Western Europe occur in several broad basins or trough-shaped areas separated by parallel anticlines or regions of elevation. The most northern of these is that which we know as the "London Basin," but which is really only part of a large trough-shaped area extending from Belgium across the North Sea, and terminating in Wiltshire; the second is known as the Hampshire Basin, and a third as the Paris Basin.

A study of all these areas is necessary for a proper comprehension of the geographical changes which took place during the period, and the stratigraphy of the Paris basin is especially important from the fact of that area lying nearer to the southern shore of the Eocene sea.

The Eocene deposits which are found in Belgium, England, and France are shown in the following table, Belgium being placed first, because sedimentation began there earlier than in England.

Belgium.	England.	France.
Wemmelian (sands)	Barton Beds	Bartonian
Laekenian, Brussellian } sands	Bracklesham and Bournemouth Beds	Lutetian
Ypresian (sand)	Bagshot Sands	Cuisian
Argile de Flandres	London Clay	Absent
Landenian { Upper	Woolwich and Reading Beds	Sparnacian
Landenian { Lower	Thanet Beds	Thanetian
Montian	Absent	Absent

A. *Stratigraphical Evidence*

The earliest Eocene deposits are those which occur near Mons in Belgium, and are known as the Montian, or Calcaire de Mons. This lies unconformably upon the highest Cretaceous strata and has a conglomerate at the base. The mass of the rock is a granular limestone, largely composed of Foraminifera, Bryozoa, and calcareous Algæ, with a fauna of Gasteropoda, Lamellibranchiata, and Echinoderms, but without any Belemnites or Ammonoids. The deposit is one formed in a clear but shallow sea, perhaps of 40 to 50 fathoms.

So far as can be judged from the small relative displacement of the Cretaceous strata, and the small difference of dip between the Eocene and Cretaceous Beds where both are inclined, the uplift of the Franco-British region seems on the whole to have been slow and equable, but at the same time the movement was more pronounced in some areas than in others, and there may also have been inequalities on the floor of the Cretaceous sea. Some portions of it were, at any rate, raised into land while others still remained submerged, and probably for a time the greater part of France and

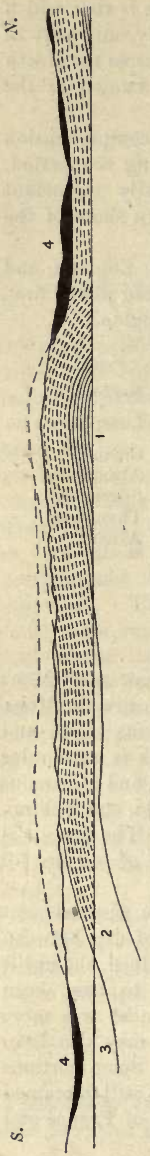


Fig. 54.—Section from Portsdown, in Hampshire, to Yattendon, near Reading.
(Scale about 5 miles to an inch. Distance, 43 miles.)
4. Eocene Beds. 2. Upper Chalk (lower zones).
3. Upper Chalk (higher zones). 1. Middle Chalk.

of the whole British region was raised into land, while a portion of the sea in Belgium still formed an area of deposition.

Moreover, there is evidence that the stratigraphical break between the Cretaceous and Eocene systems is considerable, and that the gradual rise of the Cretaceous sea-floor produced a slight upward curvature of the Chalk strata in the S.E. of England, so that a low and broad anticlinal flexure was formed over the very area which subsequently sank to receive the earliest Eocene deposits. This unconformity is shown in Figs. 54 and 55 ; the former showing how much of the Chalk was destroyed by erosion before the Thanet Beds were deposited in the London basin, the latter showing the local unconformity in Berkshire, and how the base of the Eocene passes across the edges of the slightly inclined beds of the Chalk. Fig. 55 is reproduced by permission from the *Proceedings of the Geol. Assoc.*, vol. xix. p. 395. From this overstep, and from the facts connected with the Montian deposits of Belgium, it is clear that the history of the interval between the Cretaceous and Eocene period has yet to be written.

Again, in the north-west part of the British region extensive volcanic disturbances took place at an early date in Eocene time, and that area may have continued to rise spasmodically during the volcanic eruptions which there succeeded one another, as will be described in the next chapter.

After a time, however, in the eastern and southern areas a slow subsidence ensued, in consequence of which the Belgian sea was carried westward into what afterwards became the London basin. The earliest deposits formed in the British part of this sea were the Thanet

Beds, grey sandy clays and sands, which are only found in the London basin, extending westward as far as Leatherhead and northward to Sudbury. From the clayey nature of the beds in East Kent, the abundance of glauconite grains, and the admixture of calcareous matter we may infer that the water was comparatively deep in that district, while their replacement by sharp quartz-sands as they are traced westward proves the water to have shallowed in that direction. The Thanet Beds do not occur in the Hampshire basin, nor even in the outlier at Newhaven (Sussex), where Woolwich Beds rest directly on Chalk.

The Woolwich and Reading Beds are a very variable set of deposits, and they exhibit at least three distinct facies :—

1. The first type is purely marine, and consists of light grey and greenish sands, with very few pebbles ; it is only fossiliferous

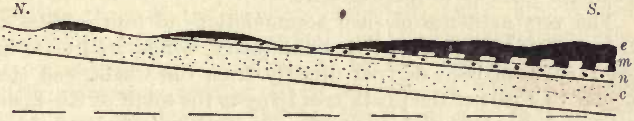


Fig. 55.—DIAGRAM SHOWING THE RELATIONS OF THE EOCENE AND THE CHALK IN BERKSHIRE (H. J. O. White).

e. Eocene Beds. *n.* Uintacrinus Band.
m. Marsupites Band. *c.* Coranguinum zone.

in East Kent, but probably passes westward beneath the Woolwich type.

2. The second type is that of the Woolwich Beds, which consist of dull or dark-coloured sands and clays, containing estuarine and freshwater fossils ; Pebble Beds of variable thickness also occur in them. This type only occurs over a certain area from Guildford in Surrey to Milton in Kent, and again at Newhaven on the southern side of the Wealden anticline ; but it would be rash to assume that it originally extended completely across the Wealden district.

3. The third and most widely-distributed type is that of the Reading Beds, which prevail throughout the central and western parts of the Hampshire basin, and through the western and northern parts of the London basin. They consist of clays and sands, which are generally bright-coloured, and sometimes contain marine fossils at the base, but in the higher beds occasional plant-remains are the only fossils ; layers of pebbly sand, often compacted into conglomerate, are of frequent occurrence, the pebbles being always of flint.

This third type can be traced into the second along the southern edge of the London basin, and the change consists chiefly in the thinning-out of the mottled plastic clays, and the setting-in of a bluish-grey laminated clay, which contains freshwater and estuarine mollusca as well as plant remains.

The Pebble Beds which form such a marked feature in the district to the south-east of London lie principally above the main mass of the Woolwich clays and sands. Eastward they appear to pass into marine sands with a pebbly base, and they have been described by Mr. Whitaker under the name of the Oldhaven and Blackheath Beds. He has also shown that during their formation erosion took place on an extensive scale, and that these Pebble Beds sometimes cut through the whole of the underlying Woolwich Beds, so as to rest upon the Thanet Sands. Moreover, it seems probable that they extended beyond the limits of these sands to the southward, overlapping them and resting directly on the Chalk, just as the Woolwich Beds do to the westward.[1]

The very existence of such accumulations of flint pebbles, to a thickness of 40 or 50 feet in some places, would lead us to infer that they have been derived directly from the Chalk, and consequently that part of the Chalk area lying to the south of the London basin was then exposed to erosion. If these pebbles had been brought by a large river from the west or south-west we should expect to find them thickening in one of those directions ; but such is not the case, indeed they actually thin out westward as well as eastward, and thus they appear to be local deposits confined to the northern side of the Weald.

The London Clay is a marine deposit formed during a further subsidence of the area. Its basement bed is always sandy and pebbly, and the lower parts of the clay are often sandy, but the highest part, as seen in the Isle of Sheppey, is a pure clay, and Mr. W. H. Shrubsole informs me that there is a sharp line of demarcation between this clay and the Bagshot Sand.

Marine shells occur throughout the London Clay in places, but in the highest beds they are mingled with fossils of terrestrial origin, which must have been transported by river-currents from some neighbouring land. These include trunks of coniferous trees, fruits of the *Nipa* palm, the fruits and seeds of other plants, with the bones of crocodiles and snakes, but the last are believed to have been sea-snakes.

Mr. Shrubsole tells me that though palm-fruits are abundant, palm-wood is scarcely ever found, and he attributes this to the fact that palm-wood is so light and dry that it floats for long distances until it finally decays and goes to pieces, while the heavier coniferous wood soon becomes water-logged and sinks

[1] *Quart. Journ. Geol. Soc.* vol. xxii. p. 419 (1866).

to the bottom, where it may be covered up by mud and so preserved.

The London Clay attains its greatest thickness (480 feet) in Essex and Kent, where the Lower Bagshots are thin, and it must have spread over a large area to the north as well as to the south of its present limits, for a boring so far north as Yarmouth passed through 310 feet of it; originally, therefore, it must have covered the greater part, if not the whole, of Norfolk, and may even exist beneath the North Sea outside the coast of Holderness, in the hollow of what may be called the Yorkshire basin.

When traced westward from the longitude of Reading and Basingstoke, the whole of the Lower Eocene undergoes such a rapid change and thinning out that we seem to be approaching a shore-line in that direction, and we certainly find the limit of the area in which the London Clay was formed. Writing on the "Western End of the London Basin" in 1862, Mr. Whitaker showed that between Hungerford and Marlborough the London Clay is reduced to a thickness of 15 feet, but is covered by a certain thickness—perhaps 40 or 50 feet—of "Lower Bagshot" Beds; near Marlborough the basement bed only of the London Clay remains, and this is directly covered by sands and pipe-clays of the Bagshot type.

In a previous edition of this work I suggested that this rapid thinning of the London Clay might be due to a replacement of clay by sand in approaching a shore-line; in fact, that the London Clay passed into and became represented by "Bagshot Sand." Mr. Osborne White, however, does not think that the facts will bear this interpretation. He points out that in this western area there is generally a pebble-bed at the base of the Bagshot Sand, which marks it off from the London Clay and indicates a change of physical conditions, so that there may even have been some current-erosion of the clay before the deposition of the sands.[1]

Mr. White remarks, moreover, that "the London Clay seems to thin most rapidly towards the north-west—that is to say, in a direction opposed to that of the dip of the rocks on the northern side of the London basin—and one is tempted to speculate whether this attenuation may not be due either to a renewal of the earlier tilting-movement indirectly responsible for the bevelling-down of the higher zones of the Chalk in the same area, or to the initiation of the disturbances which ultimately produced the London basin syncline."

With regard to the southern extension of the London Clay there is every reason to suppose that it spread completely across

[1] "Geology of the Country around Hungerford," *Mem. Geol. Survey*, p. 69.

the Wealden area and across Hampshire and Wilts into the southern basin. At Southampton and in Whitecliff Bay, at the eastern end of the Isle of Wight, the clays are about 320 feet thick, but they diminish westward, being only 70 to 80 feet in the Isle of Purbeck, and they are finally overlapped by the Bagshot Beds near Dorchester.

As already mentioned, it is only in the upper beds and in the Isle of Sheppey that the London Clay exhibits any direct evidence of fluviatile action, and it is clear that this river could not have come from the west. It might have flowed either from the east or the south, but there is no evidence in Belgium of the influx of any large river from the east, and the Belgian geologists attribute the fluviatile and estuarine portions of their Lower Eocene series to the influence of small streams from the south-east. In the same way the river (or rivers) by whose current the Sheppey fruits were carried into the London sea may have come from the southward and have drained some of the land which then occupied the larger part of France.

The Bagshot Beds are yellow sands with intercalated layers of clay; in the London basin they are nowhere more than 150 feet thick, and thin westward. In the Hampshire basin they are thicker and are less clearly divisible from the London Clay; they include layers of white pipe-clay which contain plant remains, and this facies extends as far west as Corfe and Studland in Dorset. Farther westward they pass into subangular gravel and coarse sand which near Dorchester overlap both the London Clay and the Reading Beds, so as to rest directly on the Chalk.

These Bagshot gravels contain not only flints from the Chalk, but cherts from the Selbornian and pebbles of Purbeck limestone, with many of quartz and of Palæozoic rocks which must either have been derived from the Permian conglomerates or directly from the outcrops in the west of Devon. The gravels can, moreover, be traced westward into Devonshire as far as the Blackdown and Haldon Hills, where they rest on the Selbornian Sands.

They have been attributed to a river, and supposed to be the remnants of river-gravels spread over a wide plain: their materials may certainly have been transported by rivers in the first instance, but in their present form and manner of distribution I regard them as remnants of shingle-beaches formed along a subsiding shore-line; the gravel and shingle being gradually spread out and distributed over a plain of marine erosion, like the basement bed of the Reading Beds.

The Bracklesham and Bournemouth Beds form a well-marked group, which is most fully developed in the Hampshire basin.

At Bracklesham in Sussex they are wholly marine, consisting chiefly of clays and green glauconitic sands, which yield a large molluscan fauna of a much more tropical aspect than that of the London Clay. *Nummulites* appear for the first time, and are very abundant in some of the beds, while *Alveolina* and other Foraminifera enter largely into the composition of certain layers of calcareous sandstone. At Whitecliff Bay the lower part has a more estuarine aspect, and at Alum Bay nearly the whole is estuarine and lignitic. At Bournemouth the greater part is fluviatile and freshwater, the lower beds containing a large and varied assemblage of plant remains. The Bracklesham and Bournemouth Beds were specially studied by Mr. J. S. Gardner, who wrote of the former as follows:—[1]

"The series of marine beds from Bournemouth to Highcliff, which belong to the Bracklesham Beds, are the shore deposits of the *Southern Sea*. The Bracklesham Series proper show a gradually deepening sea; for, while the beds of sand which are prevalent in the lower stages show shallow water, the clay beds above them were formed in a deeper sea, and contain deeper water mollusca. In comparing the marine fauna with that of the London Clay, its very much more tropical character is apparent. Many southern types of mollusca abound in it which are scarcely represented in the London Clay. Their aspect is completely different, and though separated geologically by but a short interval of time, hardly any species are common to both, while the lithological characters of the formation are widely and persistently dissimilar. If we examine, on the other hand, the terrestrial fauna and flora of these and the intervening strata, we see that no increase of temperature or change had taken place in the climate, and that the land was still inhabited by similar groups of reptiles and plants. It is, therefore, plain that the sea alone had changed, and become much warmer, for depression had enabled the *Southern Sea*, then occupying part of France, to advance and to overlap to a small extent the older deposits."

In the London basin the Bracklesham Beds are less developed than in Hampshire, the typical marine fauna being only found in the lowest beds, which are less than 20 feet thick. These are succeeded by fine yellow and white sands, 200 feet thick, in which layers with casts of marine fossils occur in places. They were formerly called the Upper Bagshot Sands, and are the highest beds left in the London basin; by some they are considered to be equivalent to the Barton Sands.

In Hampshire the Bracklesham group is succeeded by the

[1] *Proc. Geol. Assoc.* vol. vi. p. 96 (1879).

Barton Beds, the lower part of which is mainly clay, varying from 100 to 200 feet in thickness. Its fauna resembles that of the London Clay more than that of the Bracklesham Beds, many of the species being closely allied to those of the Lower Eocene, as if they had been perpetuated in some neighbouring province, and their slightly modified descendants had returned to the British sea as soon as conditions had again become favourable; this immigration of new species, taken together with the disappearance of the larger and more tropical-looking members of the Bracklesham fauna, is a certain indication of some important physical or geographical change.

The Upper Barton Sands seem to have been formed in gradually shallowing water, for they contain a mixture of marine and estuarine species at the top, and pass up into the brackish-water beds of the Oligocene series.

Whether the Barton Beds ever reached northward into the area of the London basin is doubtful. As a matter of fact, they are much thinner at Barton in Hants than in the Isle of Wight, and it is probable that the Barton Clay was a formation of limited extent replaced landward by sands.

Passing now to France we find Thanet Beds near Calais, Douai, and Lille, whence they evidently extended southward into the Paris basin (Sables de Bracheux, etc.), but did not reach quite so far as Paris itself. There the lowest beds are equivalents of our Woolwich and Reading Beds, consisting mainly of plastic clays, but eastward these pass into a set of sands, clays, and lignites containing some of the same fossils as the Woolwich Beds.

The London Clay, which is as thick in Belgium as it is near London, thins out southward, and is only found in France near Calais and Orchies. In the Paris basin it is represented by part of the Cuisian or Sables de Soissonnais, which do not extend to the south of Paris and die out eastward near Epernay; their maximum thickness is about 150 feet, and their upper part must be the equivalent of the Bagshot Sand.

The Bracklesham Beds are represented by the Calcaire Grossier, a limestone group containing numerous fossils. At the base there is a layer of pebbles overlain by glauconitic sands and limestones, and these by shelly and foraminiferal limestones, which must have formed in clear water at a considerable distance from land. The thickness of the group is only about 100 feet, but it evidently corresponds to the whole of the Bracklesham and Bournemouth Beds, and such limestones would be accumulated much more slowly than deposits near the mouth of a large river. The Calcaire Grossier is succeeded by sands and sandstones, with marine fossils of Bartonian type.

The French series, therefore, differs from ours chiefly in the absence of the two great clay formations, the London and Barton Clays, which are such conspicuous members of our series. The French series is consequently much thinner than ours, and all the beds, except the Calcaire Grossier, would seem to have been formed near a shore-line. The Calcaire Grossier stands out among these shallow-water beds, and marks the occurrence of an extensive subsidence, while its fauna proves that this subsidence opened the way for the immigration of a new and more tropical or southern fauna.

There is another small area of Eocene deposits in France which is of importance from its peculiar position, for, like the Bovey basin in Devonshire, it is a separate synclinal trough lying far to the west of the western border of the Parisian Eocene. This is the basin of Orglandes, in the Cotentin, where a small thickness of Eocene strata is found resting partly on the Cretaceous limestone (see p. 321) and partly on older rocks (Lias, Trias, etc.). They consist entirely of limestones—foraminiferal, shelly, and marly—the lower beds containing a marine fauna, which proves them to belong to the Lutetian division, the upper limestones being lacustrine and overlain by Oligocene clays and marls.

Here, therefore, we have a thin representative of the Lutetian which has evidently overlapped all the lower Eocene deposits of the Paris basin, just as the Bournemouth Beds have overlapped their equivalents in Dorset to reappear in Devon ; but the contrast between the extreme western deposits in England and France is remarkable, the one set being sands, clays, and lignites of palustrine origin, while the other set are chiefly marine limestones formed in the clear waters of a bay or gulf into which no river opened.

There is, moreover, evidence that this gulf extended some distance farther westward, for fossil shells of Lutetian species are sometimes found washed up on the beach at Granville (Cotentin) and at St. Malo (Ile et Vilaine), whence it is inferred that submarine outliers of Lutetian deposits occur on the sea-floor off the coast near those places.

B. *Geography of the Eocene Seas*

It is now believed that in early Eocene time the only connection with the outer ocean was northward between Scotland and Norway, a gulf from the northern ocean extending southward through the North Sea into Belgium, where the Montian deposits were being formed. The Thanetian sea was an extension of this gulf into two directions, one westward into the London basin, and one southward across Artois and Picardy into the Paris basin, the sea reaching as far west as Beauvais and Lyons la Foret east of Rouen on the one hand, and eastward as far as Reims and Rilly on the other, but not quite so far south as Paris itself.

In the Reading Beds and the Sparnacian of the Paris basin we have evidence of a further subsidence, which sufficed to carry the sea over the whole of South-Eastern England and the Hampshire basin, and southward beyond Paris into the valley of the Marne. It is clear, however, that the subsidence was not continued, and that the sea was soon blocked out of the area which it had at first occupied by the formation of sand-banks and pebble-beaches, so that the western and southern parts of the area were converted into lakes and marshes.

The Reading Beds have been described by some writers as fluviatile deposits, but they can only be so regarded in the same sense that all lacustrine deposits are fluviatile, because the material of which they are composed has been carried by streams into the lakes. That the lakes were shallow with extensive arms and inlets is very probable, and they were doubtless fed by streams which had little velocity and meandered quietly over the plains of chalk that surrounded the lacustrine area; so that parts of the water-covered tract might be regarded as expansions of the river valleys, and in that sense fluviatile.

The estuarine and freshwater beds of the Woolwich group are much more truly fluviatile, since they seem to have been formed in the estuaries and deltas of small rivers, and there is no reason whatever for supposing that these rivers came from the west, but much reason to think that they drained a tract of land over the Wealden area. They only occur over a limited space on the northern and southern sides of this area, and they are just such deposits as might be formed in the channels and estuaries of rivers which drained into land-locked bays. Moreover, Professor Prestwich states that the prevailing dip of the current-bedding in the sands of Kent and Surrey is northward, or from the direction of the presumed island, at angles varying from 10 to 35 degrees.

That the rise of the Wealden dome began in early Eocene times is by no means a new idea. It was suggested as long ago as 1852, by Professor Prestwich, in his paper on the Thanet Sands,[1] though some of the data from which he inferred its existence would not now be accepted; in 1866 Mr. Whitaker[2] remarked upon the southerly overlap of the Woolwich and Blackheath Beds, and at a later date[3] we find him inferring from this "that the planing down

[1] *Quart. Journ. Geol. Soc.* vol. viii. p. 256, and vol. x. p. 136.

[2] *Ibid.* vol. xxii. p. 420.

[3] *Mem. Geol. Survey* (1872), vol. iv. p. 241.

of the Chalk which once spread over the Wealden tract began in Lower Eocene times, and that the Pebble Beds of Bromley, Blackheath, etc., are one of the direct results of that denudation."

The existence of an island over the Wealden area will not only explain the source of the flint pebbles in the Reading Beds and the shingle of the Blackheath Beds, but will enable us to understand how the banks and beaches were formed which blocked out the sea from the interior areas over which the Reading Beds were deposited.

Throughout the time represented by this variable set of shallow-water deposits, and up to the time of the Oldhaven (or Blackheath) Beds, there was little or no actual subsidence. The conditions were those of a plain which has sunk beneath the level of the sea, and in which the connections of lakes and rivers were frequently changing, while the coast-lines were being constantly altered by the action of tides, currents, and winds, just as the eastern and southern shores of England have been altered within historic times by the same agencies, one tract of coast being worn away and cut back, while at other localities the materials so obtained were piled across the mouths of the rivers and in front of low-lying shores.

This stationary period was succeeded by one of decided and continuous subsidence, and the basement bed of the London Clay represents the final distribution of the sand dunes and shingle banks beneath the waters of the advancing sea, these barriers being destroyed, and the whole lacustrine area behind them being at once covered by the sea of the London Clay. This sea was of course shallow at first, but grew deeper as subsidence continued.

This submergence in all probability carried the Wealden island below the surface of the sea, for there seems no reason to doubt that the London Clay extended across the whole of South-Eastern England and over the north-west of France from Dieppe to Lille and Mons in Belgium. South of this line the clay passes into sands, which extend nearly as far as Paris and eastward as far as Epernay (see Fig. 56).

How far westward in England the coast-line was carried at this time is a very difficult point to determine. We know, however, that in Wiltshire the London Clay thins out, so that probably the sea did not extend very far west of Marlborough, perhaps no farther than the present position of the Chalk escarpment in North Wilts; thence it must have trended south-west to the western border of Dorset, and north-east, outside the present limits of the Chalk, to the western border of Norfolk. The great plain of the Fenland was then, of course, covered by a continuous sheet of Chalk, and there is no reason to suppose that the Eocene strata extended beyond the surface of the Chalk either westward or northward. The probable limits of the sea at this time are indicated on Fig. 56.

In the succeeding deposits of the Lower Bagshot group we have evidence of the silting up of a large part of this sea, and also for the first time we have proof of the influx of a great river, flowing from the west into that part of the Eocene sea which we now call the Hampshire basin.

The Bagshot Sands of the London basin do not exhibit any definite evidence of fluviatile action; they are probably partly marine sands, littoral and shallow water, and partly lagoon deposits; and the small thickness of marine Bracklesham Beds above them shows that this part of the Eocene sea was little affected by the subsidence which is indicated by the great thickness of the Bracklesham series in the Hampshire basin.

The Bagshot Beds of Hampshire and Dorset were evidently formed in a sinking area, where the water was kept shallow by the quantity of sand and clay poured into it by the current of a large river. Mr. J. S. Gardner was of opinion that these deposits were accumulated in a wide valley or plain near the junction of two large rivers, drawing this inference from the complexity of the stratification, which shows at any rate that there were periodical fluctuations in the volume of water, and that the currents were at times very strong and rapid. If he is right in this idea one of the rivers probably flowed down the English Channel, while the other may have come either through Devonshire or by way of the Bristol Channel.

In the Bournemouth and Bracklesham Beds we have the results of continued subsidence and of a continual conflict between the waters of the rivers and those of the sea; the latter eventually gaining the victory and spreading eastward up the estuary of the larger river. To quote again from Mr. Gardner: "In the Bournemouth Beds we have deposits of the same river, but in a more open and level valley, and in closer proximity to the sea. In all the lower or freshwater series we have no sign of the presence of sea-water, and when we do find it in the higher beds to the east, it is not that the river deposits encroached there on the sea, but that the land gradually sank, and allowed the sea to cover them." [1]

We must now turn to France and endeavour to ascertain how the Bracklesham or Lutetian sea became peopled with southern and semi-tropical forms of life. The researches of Mr. G. Dollfus along the southern side of the Paris basin have convinced him that there was a continuous shore-line all round that side of the

[1] *Proc. Geol. Assoc.* vol. vi. p. 96 (1879).

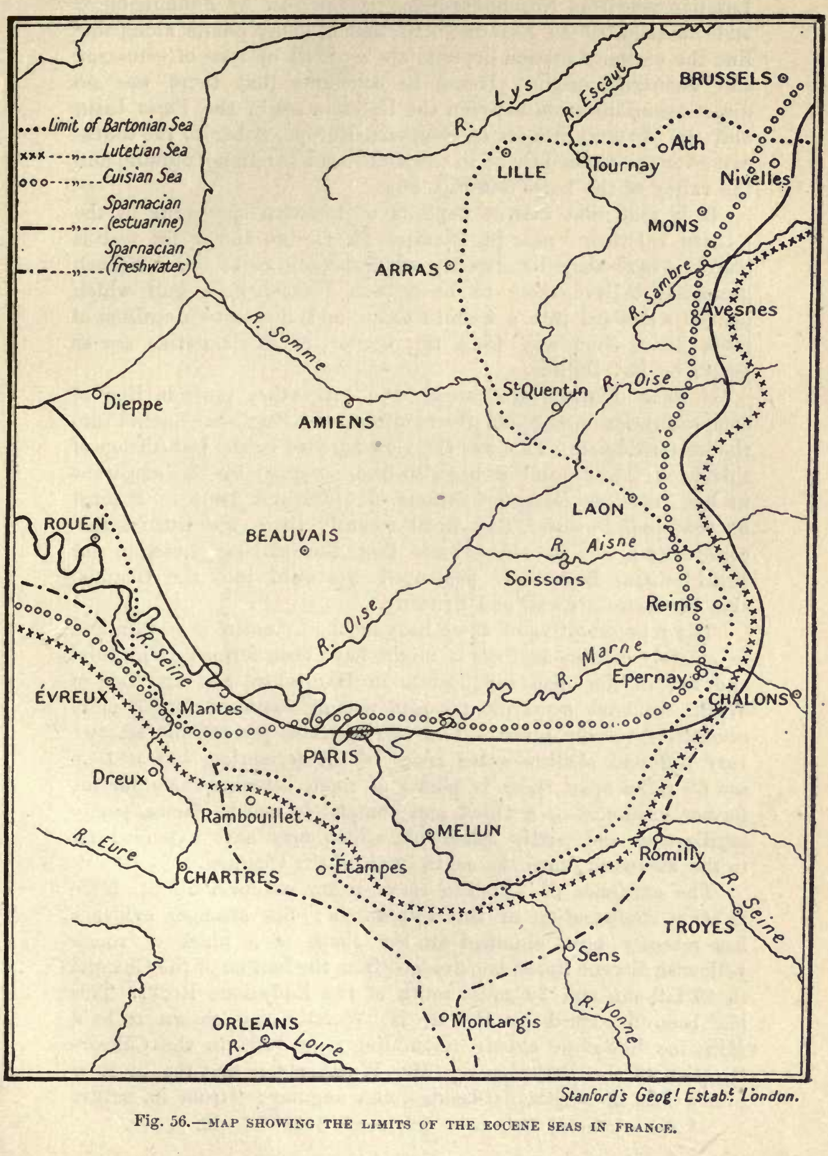


Fig. 56.—MAP SHOWING THE LIMITS OF THE EOCENE SEAS IN FRANCE.

Lutetian sea, from Nogent-sur-Seine on the east by Fontainebleau and Rambouillet to Evreux ; and that at many points along this line the marine Lutetian deposits are replaced by beds of estuarine and lacustrine origin. Hence he concludes that there was no direct communication between the Lutetian sea of the Paris basin and the Nummulitic sea of Southern Europe, either to the south-east over the Côtes d'Or or to the south-west through Touraine and the valley of the Loire (see Fig. 56).

It is true that marine deposits of Lutetian age occur in the "Loire Inférieur" near St. Nazaire, St. Gildas, and as far east as Saffré, where they lie directly on Palæozoic rocks ; but French geologists believe them to have been formed in a gulf which opened westward into a western ocean, and the eastern outliers of them are a long way from the border of the Lutetian sea as traced by Mr. Dollfus.

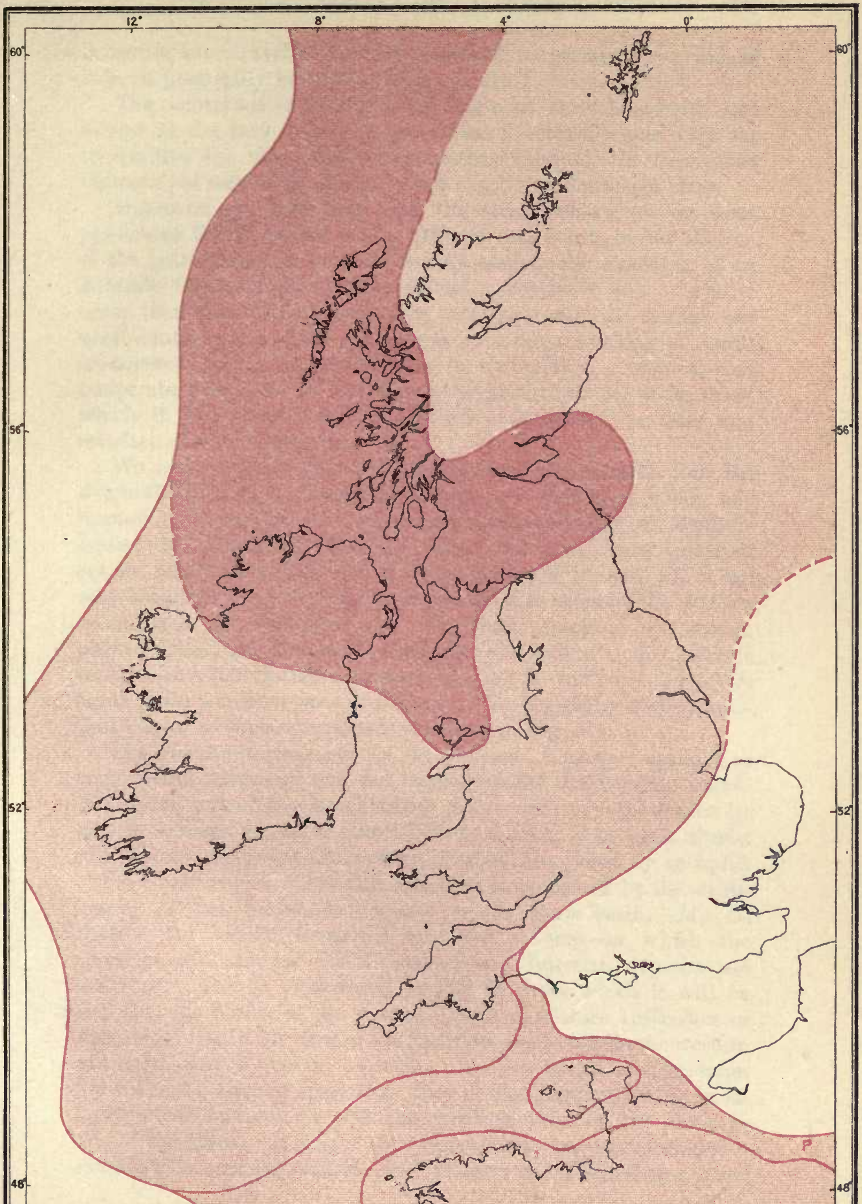
If these opinions are correct, the only other possible line of communication is through the mouth of the English Channel into the western ocean. This was the view adopted in the last edition of this book (1892), and it has also been accepted by De Lapparent in his *Traité de Geologie* (editions of 1900 and 1905). It must be confessed, however, that until recently there was little actual confirmation of the hypothesis that the marine Lutetian (or Bracklesham) Beds were prolonged westward into the Channel area between Cornwall and Brittany.

The representative of these beds in the Cotentin is so thin and so entirely calcareous that it might have been formed in an inlet and not in the open sea ; while in Hampshire and the Isle of Wight we have estuarine deposits passing eastward into a more essentially marine series. The two districts present in fact two very different shallow-water facies of the formation, but as they are 60 miles apart there is plenty of room between them for the former existence of a thick and completely marine facies, partly argillaceous and partly calcareous, which may have extended far to the westward down the central axis of the Channel.

The existence of Lutetian rocks below sea-level off St. Malo is some confirmation of this hypothesis ; but stronger evidence has recently been obtained in the shape of a block of rough yellowish Eocene limestone, dredged from the bottom of the Channel in 49 fathoms and 39 miles south of the Eddystone Rock. This has been described by Mr. R. H. Worth,[1] and shown to be a Milioline limestone closely resembling some beds in the Calcaire Grossier of the Paris basin. Mr. Worth states that the block is over a foot in length, flat-bedded, and angular ; "from its nature

[1] *Journ. Marine Biol. Assoc.* (Plymouth, 1908) vol. viii. p. 118.

Fig. 57.—GEOGRAPHY OF LONDON CLAY AND OF LUTETIAN TIMES.



London: Edward Stanford, 12, 13 & 14, Long Acre, W.C.

it cannot have travelled far and preserved its present form, indeed it must practically have been taken *in situ*."

The occurrence of such a large fragment at such a depth and almost in the very mouth of the Channel certainly goes very far to confirm the view that a connecting channel did then exist between the seas of the Atlantic and the North European areas.

Moreover, we have seen that the same western sea or ocean penetrated the European land a little farther south in the district of the Loire Inférieur, so that we may assume the existence of an Atlantic Ocean at this period, though possibly it was a smaller ocean than that of the present day, occupying only the central and north-central parts of the Atlantic area, without reaching to Arctic ice-covered lands. It would thus be essentially a tropical and temperate ocean, and in this way the tropical character of the fauna which it introduced into the British area would be fully and satisfactorily accounted for.

We must suppose that this Ocean made its entrance into the Anglo-Gallic area by breaking through the watershed which had formed the head of the east-sloping Channel-valley of Mesozoic times. No doubt the Atlantic waves had long been battering against the western land which united France to Ireland, till at last only a narrow tract of rocky land remained to separate the western ocean from the European sea. The final breaching was accomplished during the Lutetian subsidence; the waters of the Atlantic would soon widen the straits and would carry the subtropical Atlantic fauna to the southern parts of Britain. The geography of the Anglo-Gallic area, as thus interpreted, is shown in Fig. 57.

The communication between the two seas, however, appears to have been a temporary one, not lasting beyond the Lutetian epoch. The dying out of the Bracklesham fauna and its replacement by one of northern aspect, as mentioned on p. 344, is of itself almost sufficient to prove that the western channel was closed by an uplift of the whole region. But this inference is confirmed by the stratigraphy of the Bartonian deposits in the Paris basin. Mr. G. Dollfus has kindly furnished me with a map on which the approximate limits of the Bartonian and Lutetian deposits are indicated. This is reproduced in Fig. 56, from which it will be seen that the border of the marine Bartonian (Sables Inférieurs or Auversian) lies inside that of the Lutetian, especially on the western and north-eastern sides of the basin. In other words, the Bartonian Sea covered a smaller space than that of the Lutetian, owing to an uplift which was greater over the northern than on the southern side of the basin. It would thus appear that in the north-east a considerable area between the sites of Laon and Tournai was raised into land, and in all probability a still larger area was raised in the western region over and beyond the mouth of the English Channel, so that all communication with the Atlantic Ocean was closed.

By this uplift part of the Wealden area was probably again raised above the level of the sea, and Mr. Munier-Chalmas has shown that the anticline of the Pays de Bray was also raised and eroded at this epoch. The Wealden island was probably small and low, and did not extend so far west as the Boulonnais, for it seems likely that there was still communication between the Parisian and Belgian basins, both directly across the Boulonnais as well as through the Hampshire basin and across the London area to the Anglo-Belgian sea.

Finally, the characters of the highest Eocene Beds, the Barton Sands, the Sables de Mortefontaine, and the Calcaire de St. Ouen make it clear that the area of this contracted Bartonian sea was still being reduced and its waters shallowed, till large parts of it were converted into brackish lagoons and freshwater lakes.

2. Oligocene Time

A. *Stratigraphical Evidence*

The Oligocene series is a direct continuation of the Eocene series, and there was very little change in the Anglo-Gallic area of deposition from the conditions which had prevailed in the Bartonian epoch. The uplift of the western part of the area which cut it off from the western ocean was not only maintained but increased, so that the water spaces were greatly reduced and deposition was only continued in lagoons and freshwater lakes, opening into estuaries and arms of the contracting sea. Consequently the deposits are very variable, and it is impossible to correlate the different subdivisions which have been made in England, France, and Belgium with any degree of accuracy, though the general succession is the same in all three countries. Using the names which have been given to the main divisions, these may be roughly correlated as follows :—

England.	France.	Belgium.
Hamstead Beds	= Stampien supérieur	Rupelian
Bembridge and Osborne Beds	Stampien inférieur Sannoisien supérieur	Upper Tongrian
Headon Beds	= Sannoisien inférieur	Lower Tongrian

The English series is only found in the south of Hampshire and the Isle of Wight, where it is over 600 feet thick, but it must have extended for a considerable distance over the Wealden anticline in Northern Hampshire and over Sussex, though it may not have reached so far north as Berkshire or Surrey.

The Headon group is a shallow-water fluvio-marine series, consisting in the lower part of freshwater clays and limestones, in the middle of estuarine and marine beds, and, at the top, estuarine and freshwater beds. The total thickness at the western end of the Isle of Wight is about 150 feet, but the central marine beds thicken eastward, partly at the expense of the lower beds, and are about 120 feet thick in Whitecliff Bay, where the total is 212 feet. The marine band is also largely developed, and still more fossiliferous, near Brockenhurst in Hampshire, so that the deepest part of the estuary seems to have lain to the north and east of the Isle of Wight.

The succeeding Osborne and Bembridge group is a variable series of freshwater deposits with one or more layers of estuarine oyster-beds. The Osborne Beds are wholly of lacustrine origin, consisting chiefly of green clays, with thin beds of white limestone and one or two layers of lignite, from which teeth of *Palæotherium* and *Dichodon* have been obtained.

Above them is an interesting band, the Bembridge limestone, consisting of several layers of white or cream-coloured stone, often tufaceous or concretionary, and containing a remarkable assemblage of land and freshwater shells; the abundance of large land snails implying the existence of luxuriant vegetation around the lake in which the beds were formed. This lake, however, must have been very near the border of an estuary, for in the eastern part of the Isle of Wight it is overlain by a marl full of oysters, marking an incursion of the sea into the lacustrine area. The higher Bembridge Beds are marls containing shells of *Cyrena*, *Melania*, and *Cerithium*, which indicate more or less brackish water conditions.

The Hamstead Beds consist of variously coloured clays and shales, the lower part being of freshwater and estuarine origin, but the upper is more essentially marine, some of the beds containing species of *Voluta*, *Lucina*, *Natica*, etc. This group has a thickness of about 250 feet, and is incomplete, so that its original thickness was greater and perhaps more than 300 feet.

The only other district in England where beds of Oligocene age occur is that between Bovey and Newton Abbot in Devonshire. The surface of this district is a gently undulating plain, but it is in reality a basin of great depth, filled with a succession of clays, sands, and beds of lignite which have been proved by a boring to be more than 520 feet thick, and are estimated to be about 600 feet in the centre of the basin.[1]

These Bovey Beds were described by Pengelly and Heer in 1863, and were considered by them to be of the same age as the Hamstead Beds (then called Miocene). Subsequently Mr. J. S. Gardner declared that the flora they contained was the same as that of the Bournemouth Beds, and until the present year this view was generally accepted. A fresh collection and study of the plant-remains by Mr. and Mrs. Clement Reid has, however, shown that Heer was right, and that the flora is comparable to that of the highest Oligocene or lowest Miocene of the Continent, *i.e.* the lignites of Wetterau on the Rhine.

The most remarkable fact about these Bovey Beds is that the lower part, as formerly seen near Bovey, and as proved by a recent boring, consists of thick beds of lignite separated only by thin layers of brown clay; this lignitic series being more than 250 feet thick. The lignite beds are described by Pengelly and Heer as composed mainly of the trunks and branches of a coniferous tree (*Sequoia Coutsiœ*) and the fronds of a fern (*Osmunda lignitœ*). With these the seeds of a water-plant (*Stratiotes*) occur in great abundance, and it seems probable that these lignite-beds were formed in shallow water, which at times was little more than a large swamp.

The higher part of the Bovey Beds (as seen near Heathfield) are white clays and sands, the materials of which have evidently been derived from the decomposition and detrition of the granite which forms the adjoining area of Dartmoor.

Mr. Reid has obtained a large number of plant-seeds from these Heathfield Beds, and finds the flora to be practically the same as that of the lower beds, the difference being mainly in the relative proportions of the species; this was probably due to a change in the physical conditions, which may well have been an expansion of the lake and a deepening of its waters, in consequence of a greater rainfall on the Dartmoor area.

Passing over to France, a similar series is found in the Paris basin; but the exact correlation of the English and French groups is not very easy, because the frequent changes from marine or estuarine to lacustrine conditions did not occur contemporaneously in the two areas, but one was often invaded by the sea while the other was covered by fresh water. The upper gypsum beds of Montmartre are generally regarded as the equivalent of our Headon Beds; these consist of two thick masses of gypsum, evidently resulting from the evaporation of large salt-water lagoons,

[1] See *Geol. Mag.* for 1909, p. 257.

for they are underlain by other beds of gypsum interstratified with marine marls, which the French geologists regard as the highest part of the Eocene series. The highest mass of gypsum is 60 feet thick, and has yielded the bones of several genera of terrestrial mammals (*Palæotherium*, *Anoplotherium*, etc.).

The gypsum is overlain by freshwater marls, green clays with marine fossils, and again freshwater marls and limestone (Calcaire de Brie), which must be about the age of our Osborne and Bembridge Beds. Above them are the marls and molasse of Etréchy, a group which is mainly marine, and has a considerable thickness (130 to 190 feet) near Paris and throughout the northern part of the Oligocene area, but thins rapidly to the southward till it is only represented by a small thickness of freshwater marls and marly limestones.

The highest beds in the Paris basin are a set of sands and sandy pebble beds for which the old name of the Sables de Fontainebleau is most descriptive. They are almost entirely marine, and may be later than any part of our Hamstead Beds, representing a still farther southward extension of the sea. Their thickness is uncertain, but probably about 120 feet.

Before leaving France we must not omit to mention the small but interesting outlier of Oligocene in the Cotentin, so far to the west of all other traces of these deposits that it becomes a question whether it was connected with the Hampshire or the Paris basin. The lowest bed is a clay about 16 feet thick containing a small species of *Corbula* and a variety of *Cerithium plicatum*, like that which occurs in the supra-gypseous beds of Paris. It is succeeded by freshwater marls and limestones, which are considered to represent the "Calcaire de Brie," but the overlaying limestone is regarded as an equivalent of the Miocene "Calcaire de la Beauce."

The correlation of these beds with Parisian horizons must be considered as doubtful, and the Corbula clay, overlain by marl with *Nystia Chasteli*, would remind an English geologist of the Upper Hamstead Beds. It is therefore possible that the Cotentin deposits are of later date than the French geologists suppose, and in this case the superposition of the Calcaire de la Beauce would be in the natural order of succession. Finally, it may be remarked that the marine or estuarine Corbula clay is much more likely to be contemporaneous with the marine Hamstead Beds, which mark a decided subsidence, than with any part of the Bembridge group, which is so largely of lacustrine origin.

The Belgian succession is also difficult to correlate with either the British or French series, because of its more essentially marine character. The Belgian geologists only make two divisions in their Oligocene, the *Tongrian* and the *Rupelian*, and there appears to be a break and separation between the former and the highest of the beds which they class as Eocene. The Lower Tongrian appears to represent part of our Headon Beds, for it contains many of the species which occur in the Brocklesham marine band.

The Upper Tongrian consists of sands and clays from 30 to 40 feet thick, which contain a fauna of estuarine and lacustrine species (*Cyrena semistriata*, etc.), and are evidently comparable with our Bembridge Beds. The Rupelian is entirely marine and includes a thick mass of dark-grey and brown clay (Argile de Boom) much resembling our London Clay; it is from 150 to 200 feet thick, and may be regarded as the equivalent of our Hamstead Beds.

B. *Geographical Conditions*

We have seen that at the opening of Oligocene time the geography of the British region cannot have differed much from that of the last phase of Eocene geography, since the Headon Beds succeed the Barton Sands in conformable sequence, and there is still less of a contrast between the lower and upper portions of the gypsiferous group in the Paris basin. Nevertheless changes were in progress in the southern and eastern parts of Europe which led to the immigration of a number of new terrestrial animals; and thus the beginning of Oligocene time is marked by the appearance of a new mammalian fauna, while the Mollusca are obviously only the modified descendants of the endemic Eocene species.

We have also seen that while the English and French deposits have the same general character of a fluvio-marine and lacustrine series, those of Belgium are more essentially marine, freshwater and terrestrial shells only occurring at one horizon in the series. As a consequence of this difference and of the great width of the intervening area in which no traces of Oligocene deposits are found, it has been a matter of doubt whether there was any actual connection between the Belgian and the Anglo-Parisian areas.

No one has found it difficult to imagine the former continuity of the Oligocene areas in England and France, although they are separated by the whole width of the English Channel and by the width of Normandy from Dieppe to Gisors and Vernon on the Seine; on the other hand it is less easy to rid our minds of the impression that they cannot have extended over the ridge of the Artois-Wealden anticline, although the actual distance between the eastern outliers of Oligocene near Reims and the main tract near Huy in Belgium is less than the distance between Gisors and the Isle of Wight.

It must be remembered that the anticlinal arching of the Neozoic strata to their present elevations in the Weald, Boulonnais, and Artois is entirely due to post-Oligocene movements, and that the low islands which seem to have existed along this line in Landenian time must have been completely planed down and destroyed by the waves of the later Eocene seas. Hence if the Bracklesham and Barton Beds of the Anglo-Parisian region were continuous with their equivalents in Belgium, there is really no reason why the Oligocene deposits should not also have been continuous over them.

The stratigraphy of the Oligocene strata of the Paris basin is quite in accordance with this view. On its eastern side they extend quite to the confines of the area covered by the Eocene, and outliers of them are found as far north as the Soissonnais, south of Cuise and Soissons, but on the western side of the basin they do not reach so far as Evreux. In southerly directions the marine beds thin out or pass into freshwater deposits; hence it is inferred that there was no connection with southern seas on either side of the Paris basin.

Further, we have assumed that the communication with the western ocean through the English Channel was closed by elevation in Bartonian time, and there is no reason to suppose that it was reopened in Oligocene time. The marine fauna of the Headon Beds is composed to a large extent of survivals from that of the Barton Beds, and has no resemblance to that of the Bracklesham Beds. Such new forms as occur in it were probably introduced from Belgium and France.

Lastly, we know that there was subsidence in the Germanic region by which a south-eastern sea was carried over that country, and united to the Belgian sea. Whence we may legitimately infer that the initial movements of Oligocene time were uplift in the west and depression in the east, thus imparting an easterly tilt to the whole Anglo-Gallic region.

From the above considerations I am led to conclude that the small seas and estuaries of the Franco-British region were dependencies of the Belgian sea, and that it was from the latter source that their fauna was from time to time renewed or re-stocked. Further, I think that this western area of deposition opened broadly into that of the Belgian sea, as shown in Fig. 58, which is an amended conception of Oligocene geography.

The history of the minor physical and geographical changes which took place during the period can now be more satisfactorily explained. The initial uplift resulted in the conversion of the shallow sea of the Barton Sands into a group of freshwater lakes and salt lagoons ; the former lying (as might be expected) chiefly on the northern or British side, and along the extreme southern border of the Parisian area, while the salt-lagoons lay more in the middle of the region. Some of these lagoons were exposed to so long a process of evaporation and concentration that massive deposits of calcium sulphate were formed by chemical precipitation, though the stage when sodium chloride (common salt) is precipitated was not reached, and it is probable that the lakes were never completely dried up.

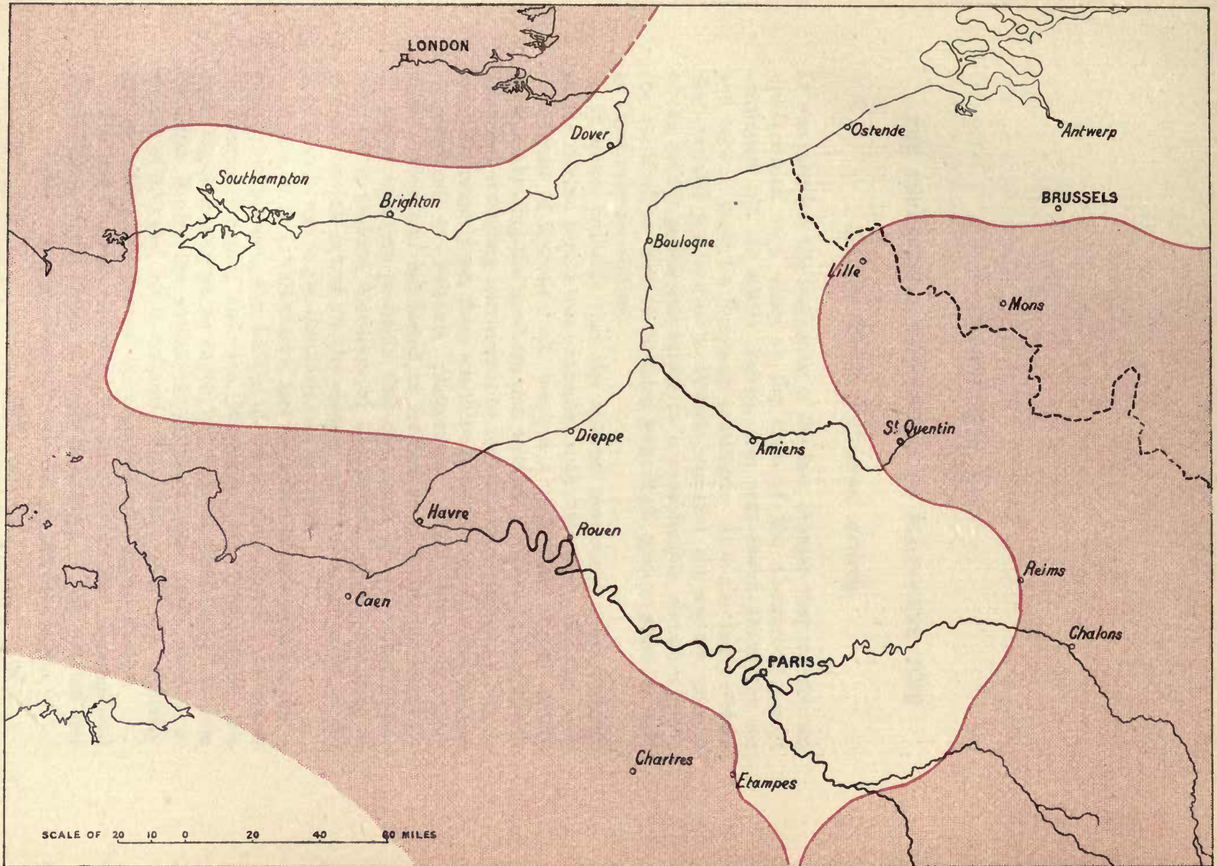
The next episode seems to have been a renewed subsidence, at any rate over the British part of the area, where the Lower Headon group is everywhere succeeded by the marine Brockenhurst Beds ; consequently we may infer that the eastern sea once more enlarged its limits, and that a large part of the swampy land, in which lay the lakes and lagoons, was submerged beneath its encroaching waters.

The phenomena presented by the Upper Headon Beds, the Osborne and Bembridge Beds, seem to represent a stationary epoch in Oligocene time, during which large parts of the Anglo-French region were silted up and again converted into a series of lakes, lagoons, and shallow water-ways into which the sea only penetrated at times of specially high tides.

Finally, there was renewed subsidence, which enabled the Rupelian sea of Belgium to spread its waters over nearly the whole of the low-lying region, reaching westward to beyond the Isle of Wight, with perhaps an inlet into the Cotentin, and southward as far as the sands of Fontainebleau have been traced. With this subsidence the history of sedimentation in the Anglo-Gallic area comes abruptly to an end.

The Bovey Beds are the relics of a lake higher up the country to the west. It has been supposed that the existing Bovey plain represents the actual Oligocene lake-basin, but the high inclinations of the strata show that it is a tectonic basin or syncline, which probably represents but a small portion of the original area of the lake. This lake may have drained southward into the sea or estuary then existing in the Channel area, or its effluent stream may have run north-eastward to join a more northern river.

Fig. 58.—GEOGRAPHY OF THE OLIGOCENE PERIOD.



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CHAPTER XIII

THE TERRESTRIAL PHENOMENA OF PALÆOGENE TIME

A. *The Region of Volcanic Activity*

It was stated at the beginning of the last chapter that the gradual uplift which took place at the close of the Cretaceous period continued till the whole British area was raised above the sea and became part of a European continent. It is also fairly certain that Ireland was united to Britain, and that the western portion of the British region was raised to a considerable elevation above the sea-level, so that it included some high plateau-areas as well as some lofty mountains.

It seems probable that the upward movement which ushered in the Eocene period was connected with the uprise of a vast mass or magma of igneous rock beneath a large area of the earth's crust, embracing the northern and western portions of the British Isles and extending northwards to Iceland and Greenland; for, as we shall presently see, there was throughout this region a tremendous development of volcanic phenomena, which began in early Eocene time and has lasted in Iceland down to the present day. It is therefore very probable that the uplift of early Eocene time was not a uniform elevation of the British region, but was of greater vertical extent in the western and northern parts of the area than it was in the southern and eastern.

Again, it is a well-known fact that our islands stand upon a submarine plateau, the border of which runs outside the coasts of France, Ireland, and the Hebrides. On this plateau the soundings are everywhere under 100 fathoms (600 feet), but from its outer border the submarine surface slopes down steeply to depths of 500 and 1000 fathoms (6000 feet), as if this declivity had for a long time formed the coast-line of Western Europe.

The late Professor Bertrand, in an essay on the "Geographical Distribution of the Eruptive Rocks in Europe,"[1] has pointed out

[1] *Bull. Soc. Géol. France* (3), vol. xvi. pp. 573-617 (1888).

that the igneous rocks of Tertiary times are principally developed in two separate and distinct regions: those of Central and Southern Europe being in close relation with the lateral pressures which produced such intense plication of the crust in that region, and gave rise to the Alpine system of mountains; while those of the north-western border were connected with what seems from a limited point of view to have been a simple uplift, but was very probably part of a larger crust-movement, which included the depression of the North Atlantic basin and the consequent creation of the present form of that basin.

The volcanic phenomena which are found within the British part of the great north-west region may be classed under five heads.

1. The system of basaltic dykes.
2. The remnants of basaltic plateaus.
3. The volcanic agglomerates and necks.
4. The intercalations of terrestrial deposits.
5. The intrusions of gabbro, granite, and rhyolite.

For a complete account of all these products of volcanic activity the reader is referred to Sir A. Geikie's *Ancient Volcanoes of Great Britain* (1897), and the Geological Survey Memoir on the island of Skye by Messrs. Harker and Clough (1904). Here there is only space for a brief description of the more important facts; and it will be convenient to give, first, a general account of the volcanic phenomena and their relations to one another; secondly, to describe some of the areas in which the rocks occur; and lastly, to indicate the sequence of events, as elucidated by the labours of those geologists who have specially studied them.

1. The Dykes.—One of the most remarkable geological features in the northern parts of Britain is the existence of numerous lava-filled fissures or dykes, which all trend more or less in the same direction, namely, from S.E. to N.W., and can sometimes be followed up hills and across valleys for distances of 50, 60, and even 100 miles. These dykes are generally filled with basalt, and vary in width from a few feet up to 100, and in some cases even 400 feet. They often stand out as wall-like masses of rock, and then form very conspicuous physical features; in other cases they have decayed more rapidly than the country-rock, and are then seen at the bottom of deep vertical clefts or trenches.

The number of these dykes increases as one passes from east to west, and is greatest in the north of Ireland and on the west side of Scotland; but they are found from Anglesey to the northern shores of the island of Lewis, a distance of 375 miles, and in the other direction from the moors of North Yorkshire to the bays of Sligo and Donegal in Ireland, a distance of more than 300 miles.

Some, and probably most, of these lava-filled fissures reached the surface and were the chief sources of the wonderful sheets of basaltic lava which will shortly be described ; others, however, did not penetrate so far upward and are found to terminate before reaching the present surface of the ground ; it is, however, quite possible that these are only portions of fissures which did elsewhere extend to the surface.

The relative geological age of these dykes is clearly shown by the manner in which they traverse all the older formations, including the Jurassic and Cretaceous rocks. It is thus evident that all are of Tertiary age, but there is also proof that they were not all produced during one volcanic episode. Some of them were the feeders of the plateau-lavas ; others cut through these lavas and even through the later intrusions of gabbro and granite, and are thus proved to belong to the latest stage of vulcanicity in the region.

2. Lava-Flows.—The first phase of volcanic activity seems to have been the production of a certain number of these fissures and the rise of a basic magma through them which welled out into the surface in enormous floods of lava. This probably occurred in many districts besides those where the basaltic lavas now exist, and the remnants of these lavas are doubtless but small portions of much more extensive lava-fields. It is possible therefore that large areas, not only between the existing remnants, but far to the east of them in Northern England and Southern Scotland, may have been covered by similar lava-fields.

The principal areas where portions of these lava-flows still remain are : (1) Antrim and Derry, (2) Mull and Morven, (3) the islands of Eigg and Rum, (4) Skye ; while far away to the north are the Faroes, which are entirely composed of basaltic lavas and their accompaniments, and form a link between the British area and the similar lava-fields of Iceland. In all these districts the lava-flows are piled one over the other, with occasional intercalations of volcanic tuff, of gravel, and of stratified lacustrine or fluviatile-deposits, while in places they have been invaded by horizontal and intrusive sills of dolerite. The result is a pile of volcanic materials which in Antrim reaches a thickness of 2000 feet, and in some of the Hebridean islands is estimated to be at least 3000 feet.

The lavas thus form extensive plateaus which still rise in some places to a height of 2000 feet above the sea, though it will be shown that they have subsided and sunk down far below the position which they originally occupied. Just as in the case of the dykes, it is evident that these lava-flows are not the products of one volcanic episode, but are the results of several or perhaps many epochs of volcanic activity. The great plateaus were evidently built up by a long succession of eruptions, but most of them seem to have occurred within the limits of Eocene time. At any rate no proof has yet been obtained that any of them occurred in Oligocene or Miocene times.

3. Volcanic Vents.—Though volcanic vents and craters were certainly formed here and there, yet no evidence of any great volcano or centre of eruption has been found, except in Arran; nor do the sheets of lava thicken toward any point which might be taken to mark such a centre. There may have been small volcanoes at intervals above some of the lines of fissure, and there were also some independent vents, the sites of which are now marked by "necks" or plugs of lava and agglomerate.

Moreover, the beds of tuff and agglomerate which occur between some of the lava-flows were probably in most cases ejected from definite craters and not from open fissures, so that they may be regarded as indicative of the proximity of vents.

In Antrim, Carnmony Hill, north of Belfast, is a neck or pipe filled with vesicular dolerite; that of Carrick-a-Rede, on the north coast, is another filled with agglomerate, and similar necks occur both in Mull and Skye. But the more extensive flows of basaltic lava seem to have issued directly from the fissures.

The most remarkable Eocene volcano is that found in the centre of Arran, where the area occupied by the complex of rocks now filling the vent is about 3½ miles long by 3 in width. Its central portion (over 2 miles in diameter) consists of a breccia or agglomerate which is largely composed of fragments of sedimentary rocks mixed with a smaller quantity of igneous rocks. This area is surrounded by a ring of intrusive igneous rocks, which are chiefly granites and granophyres.

Some of the rock-fragments in the central agglomerate are of Old Red Sandstone, and have been blown up from below, but others are masses of Trias, Rhætic, Lias, and Chalk, which must have fallen into the vent from above, and form valuable testimony to the existence of the original extension of these strata over Arran. At the same time the occurrence of Cretaceous fragments fixes the age of the volcano and of the associated igneous rocks. No remnants of basaltic lava-flows occur on the island; those erupted from this vent were probably of a more acid character, and did not belong to the earliest series of eruptions.

4. Sedimentary Deposits.—These are of great importance in determining the exact age of the lavas with which they are associated. They consist of carbonaceous clays and shales, containing leaves of terrestrial plants, which are often very well preserved, and these beds frequently rest upon sandstones or conglomerates, and are sometimes interbedded with sandy tufts and mudstones. There are also in some places layers of lignite and even beds of glossy black coal.

The intercalation of such beds with the lava-flows proves that

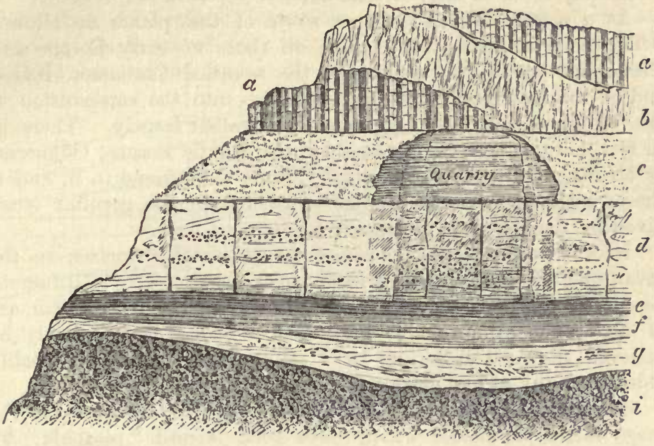


Fig. 59.—SECTION IN A RAVINE AT ARDTUN HEAD (J. S. Gardner).

a. Columnar basalt.
b. Intrusive sheet.
c. Sandstone, 8 feet.
d. Indurated gravel, 7 feet.
e. Hard mudstone with fossil plants.
f. Black leaf-bed, 2 ft. 4 in.
g. Indurated gravelly sand, 2 feet.
i. Massive basalt, rubbly at top.

the latter were poured out on a terrestrial surface, and that when they cooled streams coursed over their surfaces, carved valleys of them, and formed lakes in which sedimentary deposits could be accumulated. It has been customary to call these sediments fluviatile deposits, but leaf-beds and lignites are not often found associated with true valley-gravels and sands; it is much more probable that they originated in pools and lakes, which would almost certainly be formed on the irregular surface of the great plains of the basaltic plateaus.

A well-known example of these deposits is that exposed in Ardtun Head, a promontory on the north side of the Ross of Mull at the entrance to Loch Scridain. The accompanying view (Fig. 59) of them, as seen in a ravine cut into that headland, is borrowed from Mr. J. S. Gardner's paper. At this point the stratified beds are only 20 feet thick, but they vary up to 60 feet, and can be traced as an irregular band all across the headland, a distance of rather more than a mile; moreover, they gradually slope below the level of the sea both on the western and eastern sides of the headland, so that the area of the deposit was more extensive than the existing exposure of it. The lavas between which these beds occur belong to the lowest and oldest group in Mull, and the plant-flora is therefore likely to be of early Eocene date.

As a matter of fact Gardner wrote of the plants as follows: "The flora is distinguished, like all those of early Eocene and Cretaceous age, by the absence of the so-called Cinnamon leaves, and of the Smilaceæ, which always enter into the composition of the Middle Eocene and Oligocene floras rather largely. There is, in fact, not one type characteristic of the Middle Eocene, Oligocene, or Miocene of England or Central Europe to be found in it, and it shares with all floras of similar or earlier age the peculiar facies given by the complete absence of leguminous pods."

In Antrim stratified deposits occur at a higher horizon in the lavas, and the flora obtained from them was found by Gardner to be similar to that of the marls of Gélinden in Belgium, which are of about the same age as our Thanet Beds. Consequently he believed the Ardtun flora to be of still earlier date, and probably older than any of our marine Eocene deposits.

5. Plutonic Rocks.—The fifth group of phenomena are the large intrusive masses which have been termed "plutonic" by Mr. A. Harker, because it seems certain that they never reached the surface of the Eocene land but were consolidated under a thick cover of the previously erupted basaltic lavas. The rocks which constitute these intrusive masses are of three kinds—ultra-basic, basic, and acid; the first being peridotites or olivine rocks, the second gabbros and coarse dolerites, the third granite and granophyr. The order above stated is also the order of their relative age. The peridotites do not form any very large tracts, and are chiefly found in Skye and Ardnamurchan. The gabbros occur in Mull, Ardnamurchan, Rum, Skye, and in St. Kilda, a little island in the Atlantic 40 miles west of the Hebrides.

The gabbro intrusions have generally taken the form of laccolites, lenticular or mushroom-shaped masses formed by successive uprisings of lava, which raised the superjacent rocks and flowed laterally into the spaces thus opened. In this manner thick masses of gabbro have been built up, which in the centre are of great vertical thickness, and from which lateral extensions have been forced between the sheets of basalt in all directions and on many successive levels (see Fig. 60). It seems probable that the upper layers of the laccolite were the first to be formed, and that the mass was increased by the successive addition of lower and lower layers.

The granites and granophyres occur in several forms, sometimes in what seem to be solid bosses of great depth, sometimes as laccolites, and sometimes as intrusive sheets. They occur not only in St. Kilda and the Inner Hebrides, but also in Arran, Antrim, the Mourne Mountains, and near Carlingford.

The granites, granophyres, felsites, and pitchstones are of later date than the gabbro intrusions, breaking through them and sending a network of veins and sills both into the gabbros and the bedded basalts, and apparently in the case of the more massive

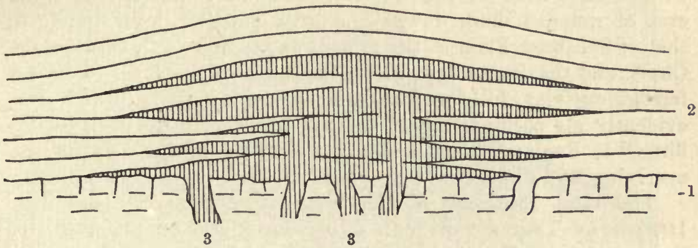


Fig. 60.—DIAGRAM OF LACCOLITIC LAVAS.

3. Pipes leading to laccolites.
2. Sheets of the earlier basaltic lavas.
1. Platform of sedimentary rocks.

granitic intrusions actually absorbing large portions of the basic materials into their own substance.

After this general description of the principal phenomena of the Tertiary volcanic rocks, the reader will be able to understand a more particular account of certain areas within the region, and of the special features which they present; he will thus gain a more complete idea of the aspect which the whole region must originally have exhibited. The districts of which brief accounts will be given are—Antrim and Derry, the Carlingford and Mourne Mountains, Arran, Skye, and St. Kilda.

North-East of Ireland.—The largest remaining portion of the Tertiary basaltic plateau is that of the north-east of Ireland; this covers nearly the whole of Antrim, the eastern part of Derry, and a part of Tyrone, and has an area of about 2000 square miles. It is not now a continuous high-level plateau, though parts of it still rise to 1800 feet above the sea; the central part has subsided and now forms the valley of the river Bann, which issues from Lough Neagh and flows northward, forming the boundary between the counties of Antrim and Londonderry.

The truncated edges of the basaltic lava-flows rise to high elevations both on the eastern and western sides of the area, whence it is evident that they must originally have extended over a very much wider region, and as the system of basaltic dykes is found over the whole of Northern Ireland, it is probable that the original plateau extended westward to and beyond the present coasts of Sligo and Donegal.

The lowest basalts of Antrim rest in most places on a floor of Chalk, but this floor has a very irregular surface, not only on a small scale but on a scale of ridge and valley inequalities; it must, in fact, have been subaerially weathered and eroded into a broad area of rounded chalk downs and intervening valleys, similar to that of Salisbury Plain at the present day. Moreover, between the Chalk and the lowest lava sheets there is always a layer of brown ferruginous clay, full of flints and pieces of chalk, which was evidently an accumulation like that known as the "clay-with-flints" in England, but baked and indurated by the heat of the overlying lava-flow.

The total thickness of the lavas of Antrim is more than 1000 feet. They are divisible into a lower and an upper group, the lower being from 400 to 500 feet thick, most of the sheets consisting of massive or amygdaloidal basalts, while the upper group are generally compact and frequently columnar. The well-known columnar basalts of the Giant's Causeway belong to the upper group, which is in places 600 feet thick, though it only remains in certain isolated areas, and must originally have been co-extensive with the lower group. Fig. 61 is a view of some of the lower basalts resting on the Chalk at Garron Point, a photograph for which I am indebted to Prof. S. H. Reynolds, F.G.S.

The two series of basaltic lavas are separated by a set of stratified beds, consisting of volcanic tuffs, clays, lignites, and iron-ores, which have an average thickness of 30 or 40 feet. These beds give evidence of a prolonged pause in the volcanic activity, during which much weathering and decomposition of the lower basalts took place, and lakes were formed in which the clays and lignites were deposited. It has already been mentioned that the affinities of the plants found in these beds are with the flora of the Lower Eocene. The associated beds of tuff and conglomerate contain many pebbles of rhyolite, as well as some of basalt, from which it is inferred that the intrusive masses of rhyolitic lava that occur at Tardree and Templepatrick belong to this inter-

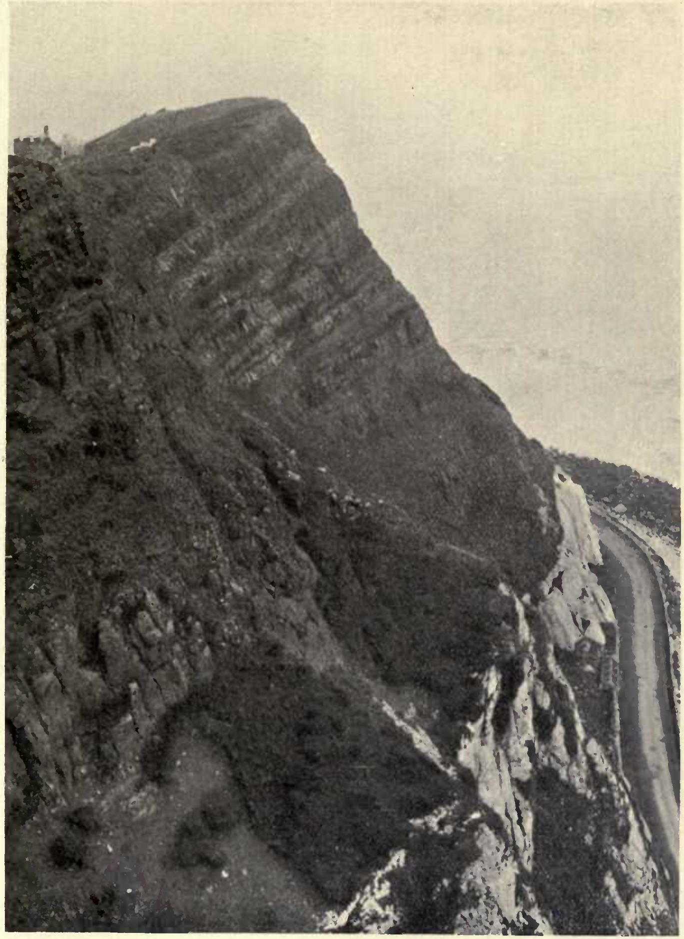


Photo *S. H. Reynolds.*

Fig. 61.—VIEW OF BASALTIC LAVAS OVERLYING CHALK AT GARRON POINT ON THE COAST OF ANTRIM.

mediate episode. Professor Grenville Cole has pointed out that while the red boles and iron-ores have originated from the subaerial decomposition of the basalts, the paler bauxites have probably been derived from rhyolitic material ; also that all the facts connected with the production of this " red zone " suggest the existence of a warm climate.

From the map (Fig. 22) it will be seen that a long tongue of the lower basalts runs southwards by Lough Neagh to Portadown and Markethill, on the borders of Down and Armagh. This points towards the mountains known as Slieve Gullion and Slieve Foye, near Carlingford. These heights are the highest points of two oval tracts of igneous rock, consisting mainly of gabbro and granophyr and rhyolite. On the south-west side of Slieve Gullion there is a remarkable ridge about 7 miles in length, which seems to have been the site of a fissure eruption of the acidic lavas. The ridge consists partly of a peculiar agglomerate and partly of andesite and rhyolite, but all traces of the erupted lava-flows have been removed by the subsequent detrition and denudation of the district; all that remains being the core of a volcanic neck at the eastern end, and the materials which consolidated over the line of fissure.

A third important tract of igneous rock is found in the Mourne Mountains of County Down, which consist of a peculiar kind of granite resembling that of Arran. The Mourne Mountains form an oval area about 12 miles long by 6 broad, with a superficies of more than 70 square miles. The granite has been thrust through Ordovician and Silurian rocks, which are traversed by basaltic dykes, and these dykes are abruptly cut off by the granite. This great protrusion seems to have taken the form of a laccolite, for it has carried upon its surface broad masses or cakes of the Palæozoic rocks with their included basaltic dykes, and the granite itself is traversed by a later series of basic dykes. These two series of dykes are believed to correspond with the lower and upper basalts of Antrim. Thus the history of events in the making of the Mourne Mountains seems to have been—first, the pouring out of the lower basalts over the surface of the Palæozoic rocks, then the rise of the granitic magma which lifted the cover of basalts, together with some thickness of Palæozoic rock, and formed a large laccolite. Finally, after an interval, other fissures were formed and filled with basaltic lava, which probably reached the surface and formed an upper series of lava-flows, as in Antrim.

It is probable, however, that the laccolite and its uplifted cover, which may have been 600 or 700 feet thick, formed a mountain ridge in Eocene time, just as it does now, and that the later basaltic lavas welled out of its sides and did not, therefore, overspread the whole mass. Even now Slieve Donard, the highest ridge, is 2800 feet above sea-level ; adding 600 feet for cover, since removed, and allowing 1500 feet for the higher general level of the country, we have 3900 feet as the probable height of the Mourne Mountains in Eocene time.

Inner Hebrides.—The island of Mull, with the adjacent districts of Morvern and Ardnamurchan on the mainland ; the small isles of Eigg, Rum, and Canna ; the larger island of Skye, with the adjacent isles of Raasay and Scalpa,—all these are clearly portions of the great volcanic area which has only been broken up into separate islands in recent geological times.

All the larger islands and tracts exhibit the same general structure and the same association of volcanic rocks—namely, an immense thickness of basaltic lava-flows, estimated to be more than 3000 feet deep in Mull and Skye, without any trace of a terminal summit plain. This great mass is pierced here and there by bosses and laccolites of gabbro, and by later intrusions of granite, granophyre, and felsite which have displaced and penetrated portions of all the older rocks. Finally, the whole series is traversed by a still later set of basaltic dykes which testify to a recurrence of fissure-forming, and probably of fissure eruptions on a long-vanished surface high above the present hills.

The largest areas of the plateau-lavas which now remain are in Mull, Morvern, and Skye ; the largest laccolites of gabbro are found in Mull, Ardnamurchan, Rum, and Skye ; the largest granophyric bosses occur in Mull, Rum, and Skye. The island of Eigg is chiefly remarkable for the curious ridge of pitchstone which rises with nearly perpendicular walls from the level of the basaltic plateau in the south-west part of the island. This was formerly supposed to be part of a lava-flow which had filled up the bed of a river; but a recent examination of the island by Mr. A. Harker has convinced him that the pitchstone is an intrusive mass, and that the subjacent conglomerate is a volcanic agglomerate partly rearranged by water action.

St. Kilda.—This small island, situated out in the Atlantic 40 miles west of the Hebrides, is a most interesting relic of the western extension of the Tertiary volcanic region. It consists entirely of intrusive rocks, merely a compound nucleus of gabbro and granophyre, both of which are traversed by dykes of basalt. Of its rocks Sir A. Geikie writes that, "down to the most minute details of structure they reproduce the features so well displayed by the gabbros and granophyres of Skye, Rum, and Mull. If it is demonstrable in the case of these islands that the intrusions have taken place under a deep cover of basalt-sheets now in large part removed, the inference may legitimately be drawn that at St. Kilda a basalt plateau once existed which has been more completely destroyed than in the other region. Not a fragment of such a plateau has survived, unless we may perhaps be allowed to recognise it in some of the basalts enclosed among the gabbro-sills."

The complete removal, not only of the basaltic cover, but of the underlying sheets of mesozoic strata, from the core of the Tertiary volcano of Arran, makes the denuded condition of the outlying islet of St. Kilda far less surprising than when Sir A. Geikie penned the passage above quoted.

History of the Volcanic Phenomena.—The succession of events which seems to have taken place in the north-west part of the British region has been most clearly and completely stated by Mr. Harker, who distinguishes three distinct and successive phases or episodes in the history: (1) a volcanic, (2) a plutonic, and (3) a phase of minor intrusions. Moreover, he distinguishes between the phenomena which were only local and those which were of regional occurrence, and points out that both may be manifested within the same episode.

Thus in Skye and in some parts of Antrim the volcanic phase began with phenomena of a local order, large volcanic vents being opened, from which violent explosive eruptions took place until a large volcano had been built up, and the vents, enlarged by successive outbursts, attained in some cases diameters of one to three miles.

"The much more important eruptions which followed had a regional extension and illustrated a totally different type in the mechanics of vulcanicity. They took the form of tranquil outpouring of lava in innumerable small flows emanating from a system of parallel fissures; and by prolonged extravasation of this kind a thick pile was built up over a vast extent of country."[1]

"In the plutonic phase regional activity was wholly in abeyance. Skye now became more clearly defined as a natural district, containing as it did one of the foci at which igneous energy was exclusively concentrated." Other centres have been mentioned on p. 863: "The events of the plutonic phase fall into three well-marked stages, characterised by ultra-basic, basic, and acid intrusions respectively." During this phase the laccolitic masses of gabbro and dolerite were formed, and towards its close came the intrusions of granite, granophyre, and felsite. In Ireland this phase included the formation of the plutonic centres of the Carlingford district and the intrusion of the great granitic laccolite which now forms

[1] This and the following extracts are from "The Tertiary Igneous Rocks of Skye," by Messrs. Harker and Clough, *Mem. Geol. Survey*, 1904, p. 420 *et seq.*

the Mourne Mountains. It may also have been marked by the pause between the lower and upper basalts of Antrim, during which the only lavas to reach the surface were of a rhyolitic character.

"The phase of minor intrusions opened with a great revival of regional activity. There was an invasion of basic magma in the form of sills, collectively of enormous volume, intruded among the basaltic lavas and the underlying strata." So writes Mr. Harker, with respect to Skye in particular; but if this episode included the second great series of fissure eruptions which formed the upper basaltic series of Antrim, it was not merely a stage of minor importance, but a second volcanic episode as prolonged and important as the first.

The last phase or episode included both local and regional phenomena. In the local series he distinguishes three principal stages, the lavas of which are respectively acid, basic, and ultra-basic, *i.e.* in order of decreasing acidity and, consequently, in reversed sequence to those of the plutonic phase. The regional series comprises a large number of basic intrusions in the form of dykes, having a general N.W. or N.N.W. direction.

Mr. Harker believes that it was toward the close of this phase that the principal faulting of the area took place, and that the latest dykes were merely subterranean intrusions along lines of fissure, but neither connected with lateral sills nor issuing at the surface. If he is right in this view, the faulting of the Hebridean area was probably a consequence of the subsidence of the area into its present relative position, so that all these phenomena—the local subsidences, the faulting, and the filling of the latest fissures—may have been to a large extent contemporaneous, all three being in progress during the gradual diminution and extinction of volcanic energy.

To the date of these final movements we have at present no clue; they may have taken place in late Eocene or in Oligocene time; and the whole area has certainly been affected by later regional movements, both of elevation and subsidence.

B. *Physiography of the Land-Surface*

We have next to consider the physical geography of the British region as a whole—the position of its highlands and watersheds, the slope of its plains, and the direction taken by the principal rivers which gathered the waters of the tributary streams and carried them to the eastern sea. It is hardly possible to do this, however, till we have formed a definite idea of the actual geographical extent of the region over which this prolonged display of volcanic activity prevailed.

Some facts bearing on this point have already been mentioned; when, however, we consider more closely the areas over which such dykes and other intrusions are most abundant, we find that they are very irregularly distributed. They are abundant throughout the central and southern parts of Scotland, and over the greater part of Northumberland; but there are none in the Lake District, nor in Lancashire, nor in the more southern parts of Yorkshire; on the other hand, in the Isle of Man they are fairly common, and in Anglesey they are numerous.[1] The possibility of a separate volcanic area in the midland parts of England will be mentioned later on.

With respect to their northern limits, Sir A. Geikie states that, though there are a certain number of the basaltic dykes in the northern parts of Aberdeen and Banff, and again in the Orkneys, these seem to be sporadic occurrences, and that there are really very few in Scotland north of a line drawn from the coast of Kincardine along the southern flank of the Grampian Hills by the head of Glen Shea and Loch Tay to the north-west coast of Argyleshire.[2] The line drawn on Fig. 57 to indicate the areas within which volcanic activity was principally developed has been drawn in accordance with the statements above made.

The western limit of the region still remains for consideration, and since we know that the dyke-seamed area includes the whole of the north of Ireland, as well as the Outer Hebrides and the little island of St. Kilda, it is clear that this western limit must have lain outside all existing tracts of land.

The continental platform on which the British Islands stand, and its termination in a steep declivity which falls rapidly into the deep basin of the North Atlantic, have been mentioned on p. 359. Reference was also made to Bertrand's suggestion that the formation of that deep basin was correlative with the uplift of Western Europe in Eocene time. I now propose to show that the lower and greater part of this declivity does run entirely outside the whole region of Eocene vulcanicity from Ireland to Greenland.

Reference to the Admiralty charts of the seas round the British Islands shows that the contour-line of 100 fathoms runs outside the western coast of Ireland, passing with a N.N.W. trend about 20 miles from Achill Head and about 40 miles from Aran Island, off the Donegal coast. Thence it runs northward, passing about 18 miles west of the island of St. Kilda and then bending

[1] See E. Greenly in *Geol. Mag.* for 1900, p. 160.
[2] *Ancient Volcanoes of Great Britain*, vol. ii. p. 121.

to the N.E., a direction which carries it outside the Shetland Isles. This line roughly defines the continental plateau, and inside it the sea-floor is everywhere less than 600 feet deep, so that an elevation of that amount alone would unite Ireland to Great Britain and convert the British region into a north-western extension of Europe.

Outside this line the depth of water rapidly increases, so that from a point west of Achill Head to one N.W. of Cape Wrath the contour of 300 fathoms (1800 feet) is reached at a distance of from 6 to 25 miles of the 100-fathom line, and in many places the contour of 500 fathoms (3000 feet) is only a few miles outside that of 300. Along this tract, therefore, there is a continuous declivity, varying in angle of slope, but often sinking rapidly from 600 to 3000 feet; in other words, from the border of the continental plateau to a depth of 2400 feet below it. These greater depths, however, are not continuous to the north of Scotland, for though there is equally deep water between the Shetland and the Faroe Islands, it is separated from the depths of the Atlantic by a remarkable ridge, known as the Wyville-Thomson ridge, which rises to within 250 fathoms of the surface.

Charts of the northern seas show that an elevation of 330 fathoms (about 2000 feet) would not only unite Scotland to the Faroe Islands but would also unite the latter to Iceland and Iceland to Greenland. As a matter of fact, Iceland and the Faroe Islands stand on a broad platform which divides the deeper parts of the Atlantic from those of the Greenland sea, and this platform is connected, by sub-marine isthmuses, with Greenland on the one hand and with Scotland on the other.

It is not here contended that any particular contour-line on the floor of the modern ocean represents the border of the European continent in Eocene time, for the submarine surfaces must have been modified by later Tertiary crust movements, just as the terrestrial surfaces have been altered, and especially may this have been the case with the areas embraced by the North Sea and the Greenland Sea (between Iceland and Norway). It is sufficient for my purpose that the great declivity which forms the western border of the continental platform is continued northward beyond the break in the 100 and 200 fathom contours and passes outside the whole region of Tertiary volcanic activity. Consequently it seems reasonable to infer that a certain part of this declivity, somewhere between the contours of 300 and 500 fathoms, roughly coincides with the north-western coast-line of Eocene Europe, and that the declivity as a whole probably dates its existence from the time of the Eocene volcanic episode.

Let us assume that the western coast-line of the British region approximated to the existing submarine contour of 300 fathoms (1800 feet). Have we any means of estimating the additional height to be allowed for in the average thickness of material removed from the area by subaerial detrition and marine erosion since Oligocene time? Or can we in any way form an idea of the average height to which the surface of this western part of the Eocene land rose above the level of the contemporaneous Atlantic Ocean before the outpouring of the basaltic lavas? I think that by a careful consideration of that portion of this surface which has been preserved in the N.E. of Ireland we may be able to do so.

In Derry and Antrim we have an extensive surface of Chalk underlying the basaltic lavas, but this surface is not now anything like a plain or a plateau; on the contrary, a section across it from west to east would show that it forms a broad and somewhat deep trough. Along an axial line running nearly north and south from Portrush and the mouth of the Bann to Lough Neagh, its surface lies below the present sea-level, while on the western side it rises to heights of 1000 to 1500 feet above the sea; on the eastern side it is more irregular, varying from sea-level in some places to 1000 feet above. Such a conformation of surface is clearly not an original one, it has undergone deformation; and I think both the greater height of the western side and the irregularity of the eastern side can be satisfactorily explained by the supposition that the slope of the original plateau was from west to east, the north and south trough being due to subsidence after the cessation of volcanic activity.

If the surface on which the earliest lavas were poured out was a high level plain with a slope and consequent drainage toward the east, the valleys which had been carved out of it during its uplift would naturally be deeper on its eastern side, and that part of the area would present a succession of ridges and valleys having a general east and west direction. The earliest lava-flows would occupy the valleys, and the eastern outcrop of the surface at the present day seems to show the intersection of such valleys and ridges, though some of the inequalities may be due to displacements by faulting and crust movement.

As a further inference from this conception of the sub-basaltic surface we may suppose that the higher parts of the western side have not suffered any great displacement from their original relative position with respect to the eastern side. The chief subsequent alterations of level have probably been the production of the axial trough and a general subsidence of the whole region.

Consequently we shall be forming a moderate estimate of the average height of the western part of the plateau if we put it at 1200 feet above present sea-level ; and as we have already assumed that the shore-line of Eocene time is now 1800 feet below the level which it then occupied, it follows that the average height of the Eocene land in the eastern parts of Derry and Tyrone was about 3000 feet. Moreover, this particular tract is not likely to have coincided exactly with the actual watershed between the rivers which ran eastward and the shorter streams which flowed westward into the Atlantic. This watershed was probably a little farther west, and its height may have been anywhere between 3300 and 4000 feet.

Some of my readers may perhaps think that such a high general level of the surface of the land in Ireland is inconsistent with the fact that in the eastern and southern parts of England the surface of the Chalk was at the same time bordering on or just below the level of the contemporaneous sea. There are, however, two considerations which will suffice to dispel any such doubts. The first is the probability that Ireland was never so deeply submerged as England ; there may have been a difference of 200 to 300 fathoms in the depth of the Cretaceous seas over England and over the N.E. of Ireland, so that a uniform elevation of the region would have resulted in a difference of level above the sea which may have amounted to 1500 or even 2000 feet. The second consideration is that the uplift was probably not a uniform one, but was much greater in the N.W. region, beneath which a vast magma of molten rock was gradually rising, than in the S.E. region, where quiet sedimentation was in progress.

When these facts are borne in mind, it will be seen that an elevation of 3000 feet for the plateau of N.E. Ireland is quite a reasonable estimate, and that many parts of Ireland and of the Hebridean area may have risen to greater heights than 3000 feet before the volcanic eruptions began.

I see no reason to doubt that the Cretaceous rocks extended over the greater part of the whole northern region which I have supposed to be land in Eocene time ; certainly over the north of England and the northern part of the Irish Sea, over large parts of Southern Scotland, over the whole of the Scottish Lowlands, and lastly, over the whole Hebridean area. Neither do I see any improbability in supposing that the emission of basaltic lavas took place over all the areas where basaltic dykes are now abundant, and also over the greater part of the vanished western land ; perhaps even to the very western coast-line above the great submarine declivity in the modern Atlantic Ocean.

Here I find myself compelled to differ from the view expressed by Sir A. Geikie, in whose opinion the area of lava-covered country was of much smaller extent. He supposes the lava-field to have been limited to the ancient gulf or depression between the Outer Hebrides and the Scottish Highlands, and evidently thinks that this was still a broad valley or lowland area in Eocene time, and that the lava-flows filled it without passing beyond its borders. He estimates the width of this area at from 20 to 50 miles, with a length of about 250 miles, so that he computes the whole area to have been only some 7000 to 8000 square miles.[1] He refers to the ancient history of this depression, adding that "sheet after sheet of lava was poured out, until several thousand feet had accumulated, so as perhaps to fill up the whole depression, and once more to change entirely the aspect of the region."

My view of the case is that the region had lost its ancient aspect before the outpouring of the lavas, that this ancient valley had been completely or almost completely filled up by the succession of Jurassic and Cretaceous rocks which had been deposited in it, and that these strata (especially the Cretaceous) spread both eastward and westward beyond the limits of the Triassic gulf. That they spread over the Isle of Arran has been proved by the masses of Lias and Chalk which lie in the old volcanic vent of that island.

No doubt the Mesozoic rocks were subjected to much erosion, both marine and subaerial, during the elevation of the country at the close of Cretaceous time. This is demonstrated by the small thickness of them that remains in many places beneath the Eocene basalts, and by the entire removal of them in some localities; but I see no reason for supposing that the whole of the ancient valley or gulf had been re-excavated to such a depth as to accommodate a thickness of 3000 feet of lava-flows, tuffs, and sills, or for supposing that the lava-field was restricted to such a narrow area as that between the Outer Hebrides and the Highlands.

Sir A. Geikie is himself of opinion that the great central or axial depression of the Antrim plateau is the result of post-volcanic subsidence, and he also admits that there have been great subsequent and differential subsidences in the Hebridean area. Subsidence after a volcanic episode is just as frequent as elevation of an area at the beginning of such an episode; it is therefore highly probable that the long depression now occupied by the volcanic rocks of the Inner Hebrides is due to a subsequent subsidence of this tract, analogous and parallel to, if not continuous with, the similar depression of Antrim.

[1] *Ancient Volcanoes of Great Britain*, vol. ii. p. 181.

On this view the Inner Hebrides are merely the local remnants of a vast lava-covered area which stretched far to the westward over the Outer Hebrides, over St. Kilda, and over all the sea-space which lies between these islands and the coast of Donegal. Consequently I would estimate the width of the conjoined Hebridean and Hibernian lava-fields at about 120 miles, and their length from the Carlingford Mountains to the Butt of Lewis at 300 miles, giving an area of 36,000 square miles. To this must be added the eastern area, which was most probably the scene of similar eruptions, though only the lava-filled fissures now remain; that of Central with parts of Southern Scotland, which, on a moderate computation, would include an area of 11,000 square miles. Thus the total area of lava-covered country at the close of the later volcanic episode may have been nearly 50,000 square miles.

Although a lava-field of this size may seem a large one, yet in reality it is much smaller than some which still exist. Thus the space occupied by the Deccan traps of India has been estimated to be about 200,000 square miles; and the lava-fields of Idaho in North America are said to cover an area which is larger than the whole of France, that country having an area of 200,700 square miles. Finally, the British volcanic area may be compared with that of Iceland, which consists wholly of similar lavas, and has an area of about 45,000 square miles. Moreover, Iceland is obviously but a remnant of a far larger area of volcanic material, for its lavas are believed to be from 8000 to 10,000 feet thick, and their base is nowhere visible. No one doubts that it was once united to the Faroe Islands, and the submarine platform on which both stand, roughly measured to the contour of 300 fathoms, will be found to have an area of 175,000 square miles.

What, then, was the scenic aspect of the region during the formation of these vast lava-fields? This we can partially realise from the descriptions which have been given of the great lava plains of Western North America, in Idaho, and Utah. Those of Idaho are thus described by Sir A. Geikie: "We rode for hours by the margin of a vast plain of basalt, stretching southward and westward as far as the eye could reach. It seemed as if the plain had been once a great lake or sea of molten rock, which surged along the base of the hills, entering every valley and leaving there a solid floor of bare black stone."[1] This great plain has been deeply trenched by the streams which traverse it, and especially by the Snake River, which flows in a gorge or cañon from 500 to 700 feet deep; the numerous streams which issue from the

[1] *Geological Sketches at Home and Abroad* (1882), p. 272.

mountains on its northern and eastern margins are soon lost in cracks and fissures, so that the greater part of the plain is a bare and barren waste. Here and there a small cinder cone rises from the surface of the plain, but no volcanoes of the Vesuvian type are anywhere to be seen.

Parts of the British region may have corresponded with the above description, but it differed in possessing a certain number of volcanic vents, some of which must have been of considerable size, for in some cases the neck or funnel which opened upward into the crater has a width of 2 or 3 miles. Such a vent must represent a mountain of several thousand feet in height, for when the crater of Vesuvius was less than a mile in breadth, the mountain was about 4000 feet in height.

Another point in the scenery of the British volcanic region was the abundant growth of vegetation, which could only have been made possible by a copious rainfall. The surface was doubtless traversed by many streams, and seems also to have been dotted with pools and lakes, around which grew the trees, bushes, and other plants which furnished material for the lignites and plant beds which occur in many places. That the climate was damp and warm is attested by the formation of laterite and bole in Antrim, and by the seams of red ferruginous clay which so often form partings between the basalt sheets of Mull and Skye, for it is only under such conditions that basalt decomposes into such ferruginous soils.

We may therefore picture a country in which all the terrestrial agents of change were in full activity, a country where fire and water frequently contended for the mastery, where wide districts were from time to time devastated by streams of lava, but were soon restored to fertility by cooling showers and by the irrigation of a thousand streams that sprang from the slopes of cloud-capped mountains.

Finally, we may endeavour to restore the geography of that part of the British region which lay between the northern area of volcanic activity and the south-eastern area of sedimentation. We know that most of the chief orographical features of the country had already been developed. The hilly districts of Southern Scotland, Northumberland, and Wales must have risen as highlands above the great plains of Chalk by which they were more or less surrounded; for all these mountain districts must have then been actually higher than they are now by just that amount of material which has been removed from them during Miocene, Pliocene, and Pleistocene times.

Little, however, has yet been said about the development of the Pennine range or of the Cumberland and Westmoreland Hills. Both were referred to in Chapter VIII. as having been the scene of disturbance and faulting, with some elevation in pre-Permian time, and it has generally been supposed that the Pennine range attained its complete development between the Permian and Triassic periods. Moreover, it was assumed that its height was then so great that it continued to form a barrier between two areas of deposition throughout the Jurassic period.

More recent consideration of the stratigraphical relationships of the strata which lie on each side of the range has thrown doubt on this supposition, and when discussing the westerly extension of the Cretaceous deposits we had occasion to consider the probable age of the Pennine anticline and of the flexures which diverge from its southern end (see p. 328). From the facts then stated it was inferred that these flexures were not then in existence, and that they were all produced in Tertiary times.

The question therefore now arises, Did these important features come into existence in the Eocene period, or at some later epoch of Tertiary time? It is not very easy to form a definite opinion on this point, and indeed, so far as I know, it has never been adequately discussed. Dr. Marr, writing in 1906, came to the same conclusion as I have done with respect to the final uplifts of the Lake District and Pennine area, namely, that the movements which made these districts the dominant watersheds of the north of England were geologically contemporaneous, and occurred in Tertiary time.[1]

Dr. Marr, however, was inclined to place the date of these uplifts in the Miocene epoch, but the determination of their exact age was not important for the purpose which he then had in view, and it requires a more careful consideration than he gave to it. Moreover, he has himself pointed out certain facts which tell strongly in favour of an Eocene date. He remarks that regular dome-shaped uplifts like that of the Lake District dome are very often, if not invariably, produced by the intrusion of a laccolitic mass of igneous rock. Further, though no such laccolite is actually exposed in the central dome, the olivine-dolerites of Carrock Fell and of the Skiddaw area are strikingly similar to those of Eocene date in the Hebrides, and these rocks occur in what appear to be subsidiary domes, and are certainly part of the general uplift.

Let us now see what can be said against the view of their Eocene age. Dr. Marr remarks that the Eocene upheaval does not seem to have produced much differential elevation; but the London basin overlies an anticlinal arch of Chalk from which

[1] Pres. Address, *Quart. Journ. Geol. Soc.* (1906) p. lxxxvi *et seq.*

more than 500 feet of chalk must have been removed before Eocene sedimentation began. A stronger argument is found in the fact that no basaltic dykes occur in the Lake District, and only a few in the northern part of the Pennine range; whereas we should have expected such dykes to be frequent in areas connected with Eocene vulcanicity. Lastly, though the dome of the Lake District could have been produced by a laccolitic intrusion, the long chain of the Pennine Hills could not.

These difficulties may be met by the following considerations. The absence of the prevalent basaltic dykes would only mean that these areas were not included in that of the first phase of Eocene vulcanicity, and were not covered by mantles of basaltic lavas. The intrusion of laccolites was a later phase in the history of the volcanic region, and it is possible that the ridging up of the Pennine chain belonged to a still later phase, indeed to the last volcanic episode, when subsidence of the central volcanic areas had commenced.

This leads us to another line of argument; for although the Pennine range terminates southward in Derbyshire and North Staffordshire, it does so in a peculiar manner. The central and eastern parts of the anticline pass beneath the Triassic deposits, but Carboniferous rocks emerge again in the form of several minor diverging ridges, those of the Leicester, Warwickshire, Staffordshire, and Shropshire coalfields, which are separated by broad, faulted, and rather shallow synclines of Trias.

Now it is remarkable that in three of these anticlinal ridges there are intrusions of olivine-dolerite which closely resemble the peculiar Eocene dolerites of the north-west region. Professor Watts has drawn special attention to this fact, and to the probability of their Eocene age, remarking that "a broad belt may thus exist along which Tertiary vulcanicity endeavoured to assert itself wherever weak places existed, as manifested by the protrusion of ancient rocks along the belt."[1] The belt referred by Professor Watts is an area extending from Radnor to Leicestershire, *i.e.* from S.S.E. to W.N.W., but this remark does not bring out the real relations of the igneous intrusions to the ridges between the Triassic synclines.

The volcanic rocks of Tertiary type occur at the following places. One remarkable group is found near Old Radnor and Kington, some of these being acid rocks—felsites and granophyres, like those of the Plutonic phase in Skye and Rum; others are basic (gabbros and augite-diorites). Some distance to the north-east, near Little Wenlock and the Wrekin, olivine-dolerites occur

[1] *Proc. Geol. Assoc.* vol. xix. p. 180 (1905).

which cannot be distinguished from those of Antrim and the Hebrides. Prolonging this line still farther to the N.E. we come upon a remarkable dyke of olivine-basalt, which runs for 8 miles from Norton Bridge to the N.N.W by Swinnerton and Butterton. It cuts through both Bunter and Keuper divisions of the Trias, and is almost certainly of Eocene age.

Within the area of the South Staffordshire coalfield several intrusions of olivine-dolerite occur, and Jukes long ago pointed out that they were post-Carboniferous, and had been affected by the latest earth-movements impressed upon the area. Professor Watts remarks of these, that "such movement may well be Tertiary in date, as it cuts into the neighbouring Jurassic rocks, and is parallel to faults and folds which traverse more distant Cretaceous and Eocene rocks." Lastly, in Leicestershire a similar rock is intruded between Coal-measures and Trias, probably along a line of fracture produced in Tertiary time.

Thus both lithological characters and stratigraphical evidence combine to make it very probable that volcanic action manifested itself in these Midland counties in the Eocene period, but the volcanic force probably expended itself in the intrusions and in local uplifts without leading to surface eruptions. Hence it seems very likely that movements were produced along the lines of weakness furnished by the older Caledonian, Malvernian, and Charnian flexures, and this would account for the apparent transition from the single Pennine arch to several divergent lines of flexure; the whole area being then, of course, covered by a thick mantle of Jurassic and Cretaceous strata.

The connection between the Pennine anticline and the lesser flexures of the Midlands must at present remain uncertain, but there is yet another point of view from which the age of the former may be regarded. If the broad arch of the Pennine axis was not formed till the Miocene epoch, how does it come to pass that the range has so ancient an aspect, that it presents such a completely dissected surface with a well-established valley-system cut back to a narrow and irregular line of watershed? If the history of this part of England, as given in previous chapters, is correct, the thickness of Mesozoic strata overlying the Palæozoic rocks of the Pennine ridge at the beginning of Eocene time must have been very considerable; and unless the anticlinal was produced early in Tertiary time, so great a thickness of cover could hardly have been removed before Pliocene time, when we have evidence that the Carboniferous rocks of Derbyshire were exposed.

Here, therefore, it becomes necessary to estimate the probable thickness of the strata which we believe to have passed over the Pennine area. A ridge of Palæozoic rocks was formed along this line in the interval between Carboniferous and Permian time, but was broken by east and west flexures soon afterwards, and again raised to some extent before the Triassic period. In Triassic time, however, it underwent detrition, and was probably reduced to a series of low ridges and escarpments, consisting of Millstone Grit and Carboniferous Limestone, the upper parts of which were probably not far above the highest points of the present surface.

The whole tract of country then sank beneath the waters of the Keuper lake, but though the Keuper deposits are from 800 to over 1000 feet thick on both sides of the area, the thickness over the intervening ridge may not have been more than half that amount: let us put it at an average of 500 feet. This would be succeeded by the Lias and other Jurassic deposits, for which the following are moderate estimates:—

	Feet.
Upper Jurassic clays, etc.	800
Middle Jurassic limestones, etc.	200
Lower Jurassic (Lias)	1000
Keuper marls	500
Total	2500

During the Purbeck Wealden interval the whole area became a land-surface, and some erosion may have taken place, but as it was certainly a low-lying plain, the amount removed was probably small. It was again submerged by the great subsidence of Upper Cretaceous time, and some of the Jurassic clay may have been planed off by marine erosion before the accumulation of Chalk commenced. Let us assume that 300 feet were thus removed, reducing the cover to 2200 feet.

Finally, we have to estimate how much Chalk may have been deposited thereon. In Yorkshire the total thickness of Chalk is believed to be 1300 feet, with a denuded surface; consequently we shall be well within the mark if we suppose that the thickness left over the Pennine area was 1000 feet. This brings the total to 3200 feet, and there is no occasion to allow for erosion during subsequent uplift into Eocene land, because it is not likely that such erosion would be greater over that area than over Yorkshire, where 1300 feet still remain.

By the early Eocene uplift the north of England was presumably converted into a plain which had a gentle eastward slope, and on such a surface the subaerial agencies of erosion and detrition would not have much scope for action. When, however, the Pennine axis began to rise across the natural lines of drainage these agencies would come into active operation. We have seen that the thickness to be removed before reaching the surface of the Palæozoic rocks was about 3200 feet. If the rise of the axis began at the close of the Eocene or early in the Oligocene epoch, it is quite conceivable that the lapse of time from then to the Upper Pliocene would be sufficient for the accomplishment of the work, but if it only dated from the Miocene the time would be too short. Thus all lines of argument point to a pre-Miocene date, and suggest either a late Eocene or early Oligocene age for the formation of the Pennine uplift.

Let us now briefly consider some of the adjacent areas. With regard to Wales, it is probable that during the initial Eocene elevation and the period of volcanic activity it was still united to Ireland, and that the Irish Channel was not then in existence. As a matter of fact, no one has yet ventured to assign a date to the Irish Channel, but it is not unlikely that both it and the western part of the Irish Sea originated in a broad trough or depression formed as a consequence of the subsidence which so often takes place on the cessation of regional volcanic activity.

We do know that a similar broad depression was formed on the western side of Scotland in the Hebridean area, and that it either extended southward into Antrim or else that there was another area of subsidence in the N.E. of Ireland. Reference to a map of the British Islands will show that the western part of the Irish Sea is very nearly in line with the Hebridean trough, and may therefore have originated in the same manner. We have seen also that Mr. Harker believes that the faulting and settling down of the north-western area began before the extinction of volcanic activity, and was in progress during the last episode of "fissure injection" (see p. 359).

Whether there was any contemporaneous subsidence on the eastern side of England which helped to ridge up the intervening Pennine tract can only be a matter of speculation ; but there is this to be said, that at the time of the London Clay the area of deposition may have extended as far north as the basin which is indicated in Yorkshire by the eastward trend of the Chalk escarpment towards Speeton, and that this basin may have continued to exist till Oligocene time, for the Rupelian of Belgium greatly resembles the London Clay, and may have had a similar northern extension.

If the physical history of the Eocene and Oligocene epochs has been correctly interpreted in the preceding pages, it is clear that the features of the British region underwent great and important changes during this period of time. It becomes a question whether the river systems which must have been developed in early Eocene time and during the volcanic episodes in the north-west, could have continued to exist through Oligocene time after the Pennine uplift. Let us examine the probabilities of this matter.

In the early part of Eocene time, when the western areas had been raised into an elevated plateau, the watershed of which may not have been very far from the western coast-line, we may reasonably suppose that the prevalent direction of the main rivers was from west to east.

We saw reason to think (p. 373) that a considerable amount of erosion and valley-making took place in the north-west region before the commencement of the volcanic episodes, and that the watershed probably lay over parts of Tyrone and Donegal, and may have extended northward to the ridge of the Outer Hebrides. If this was so we may suppose that the streams originating on the eastern side of this watershed made their way eastward, those from the northern parts of the region combining to form a river which ran eastward across the Scottish Lowlands; while those rising in the north of Ireland would be joined by tributaries from North Wales and the southern uplands of Scotland to form a river which flowed eastward across the north of England. This river would flow over the plains of Chalk which we have supposed to have then covered Lancashire and the site of the future Pennine chain, and so into the Eocene sea, which, at any rate in the time of the London Clay, probably reached as far north as the eastern parts of Yorkshire.

Lastly, we may imagine a third great basin of drainage formed by land which connected Cornwall with Ireland and Devon with South Wales. The streams of the south-western area may have formed more than one river, but the largest one probably ran through what is now the Bristol Channel and a lesser one across the central part of Devon, possibly uniting their waters somewhere in the south of Somerset.[1] Still farther south a river must have occupied the valley of the English Channel, flowing eastward until it was submerged by the Lutetian sea and converted into a narrow strait leading from the Atlantic into the inner sea of the Anglo-Gallic region.

When, however, the western areas began to subside and the Pennine ridge began to rise above the level of the great northern plain, the drainage system may have undergone very considerable modification. It is, of course, possible for a strongly-flowing river to keep its channel open through a slowly-rising anticline, but to do so it must have a powerful *vis a tergo* in the shape of a high

[1] See A. W. Clayden's *Scenery of Devonshire*, p. 173.

watershed at no great distance, whereas in this case we are assuming a contemporaneous subsidence between the watershed and the rising anticline. Under such circumstances it is almost certain that the river would be diverted into some easier way of escape.

If such a diversion of the rivers rising on the north-west plateau took place it would almost certainly be into the newly-formed depression of the Irish Channel, and we may suppose that this depression continued southward till it reached the Atlantic somewhere to the west of Cornwall; so that from this time forth the drainage of Wales and the west of England, as well as that of Eastern Ireland, was conveyed southward to the Atlantic.

That of the Midland area, however, still remains for consideration, and in some respects it is a more difficult problem, for if the Midland flexures were not formed in early Eocene time the direction of its drainage would have been determined by rivers rising on the Welsh Highlands and flowing over a plain which sloped east or S.E.; and these Welsh rivers might have kept their original courses open throughout the whole period of time.

I strongly incline, however, to the opinion that the flexures were coeval with the epoch of volcanic activity, that the elevatory movement ridged up the Chalk into a kind of compound dome, of which the main components were the parts overlying the South Staffordshire and Warwickshire coalfields. It seems probable also that the fault which forms the western boundary of the Trias along the line of the Malvern and Abberley Hills was formed at the same time; thus increasing the depth of the synclinal depression which was developed between the Midland ridges, which have a Malvernian strike, and the more western axes in Shropshire, Radnorshire, and South Wales, which have a Caledonian strike.

In this manner a watershed would be formed in the centre of England, running for some distance in a north and south direction, and represented at the present time by the high ground in South Staffordshire and in the ridge of the Lickey Hills. We may imagine this old Eocene watershed to have passed southward across the Avon valley and parallel to the faults which cut both Trias and Lias, till it sank southward beneath the Eocene sea. If this view is correct it would be this uplift in the Midlands which determined the north-western limit of the Eocene sea, and also the strike of the Cretaceous and Jurassic escarpments as they gradually came into existence during the subsequent detrition and denudation of the area in Oligocene, Miocene, and Pliocene times.

Some corroboration of this view is found in the fact that the Lower Eocene, and especially the London Clay, thins toward the north-west,[1] and that at the same time their basal plane passes transgressively from higher to lower zones in that direction.[2]

The depression on the western side of this Midland uplift would naturally become the valley of a river which we may regard as the primitive Severn. It would probably have its sources over the area which is now the Forest of Wyre and the Kidderminster district, and it would receive strong affluents from the Welsh borders. Flowing southward it would become itself a tributary of the river, which is supposed at this time to have occupied the valley of the Bristol Channel and to have taken an easterly course to the sea over Dorset.

On this point of a central watershed running north and south through Central England and throwing off streams to the west and east, I find myself in general accord with Dr. A. Strahan,[3] but I differ with regard to the date of the uplift, which he takes to be Miocene. In his paper on the "River System of South Wales" he only discussed movements along the Caledonian, Charnian, and Armorican lines, omitting any consideration of the Malvernian line, which is exactly the direction of the central flexures and faults, and of the Midland watershed. Consequently his table of axes and directions is imperfect.

Again, I connect the later movements along Caledonian, Malvernian, and Charnian lines with one another as contemporaneous movements along old lines of weakness, and think it very unlikely that any one of them, such as the Caledonian in South Wales, should have been contemporaneous with the Miocene Armorican folding. Lastly, if the Midland uplift were of Miocene date, what of the river-courses which must have been established across it in Eocene and Oligocene times?

I think the Midland uplift antedated that of the Pennine area, but it is very likely that all the differential movements were accentuated and increased when the latter uplift took place. Thus the movement which raised the Pennine ridge at the close of Eocene time may not only have affected the Midlands, but have prolonged the watershed southward across that part of the Eocene sea-floor which was then being raised above sea-level. In this way a low watershed would be carried southward through Gloucestershire and North Wilts to the Marlborough Downs, where we find an elevated plateau which is still a watershed between streams running westward into the Bristol Avon and valleys opening into that of the Kennet, which is a tributary of the Thames.

[1] See H. J. O. White, *Geology in the Field*, p. 227 (1910).

[2] See *Ibid.* "Geology of Country around Hungerford," *Mem. Geol. Survey*, 1907, p. 45.

[3] *Quart. Journ. Geol. Soc.* vol. lviii. p. 2 (1902).

These two rivers may not actually have come into existence until after the production of the east and west flexures in Miocene time, but it looks as if the north and south axis was here truncated by the subsequent uplift of Southern England along the Armorican lines, just as the Caledonian axes are truncated by the same Armorican flexures in South Wales.

CHAPTER XIV

THE MIOCENE EPOCH

No Miocene deposits of any kind have yet been discovered in the British region, and beds of Pliocene age only occur in the east and in the extreme south-west of England. There is, therefore, a great gap and geographical break between the Oligocene and the Pliocene of this country, and we are compelled to suppose that during the intervening Miocene epoch the whole region, as well as a large part of the North Sea area, was dry land and was raised to a higher general level above the sea than that at which it had previously stood.

At the close of the Oligocene large areas of the British region must have been covered by Eocene and Cretaceous deposits, and other large areas by volcanic rocks of Eocene and possibly also of Oligocene age. During Miocene and Pliocene times several thousand feet of rock-material must have been removed from some of these areas, so that, as far as the British region was concerned, the period was one of destruction rather than of construction. At the same time the region was not stationary throughout its duration, nor were subterranean forces entirely inactive ; on the contrary, differential movements led to the development of some important physical features which had not previously been in existence.

A. *Miocene Deposits*

Although no Miocene deposits have been found in the British Isles, some occur in the neighbouring countries of France and Belgium, so that we are not without a record of the kind of sedimentation which took place in parts of Western Europe. Moreover, some of these are marine deposits and some are lacustrine, and their relative positions furnish us with evidence of some of the events and changes which took place during Miocene time.

French geologists recognise no fewer than six successive stages or zones in the Miocene deposits of their country, but for my present purpose it will simplify matters to group them in three divisions, which may be called Lower, Middle, and Upper. The following is a tabular view of the deposits so grouped :—

	North of France.	Belgium.
Upper	Sands with Cardita striatissima, etc.	Sands with Pectunculus pilosus.
Middle	Faluns of Anjou. Faluns of Touraine.	Sands with Panopea Menardi.
Lower	Sands of the Sologne and Orleanais.	Sands with Melongela cornuta.
	Calcaire de la Beauce.	Sands and gravel at base.

The most notable fact with regard to the French deposits is that those above grouped as Lower Miocene are entirely of fresh-water origin, marine beds of this date only occurring in the southern area of Aquitaine and in other parts of Southern Europe. On the other hand, the beds of Middle and Upper Miocene age are wholly marine, and they only occur in the western part of the region; the Middle Miocene indicates a subsidence of that area, which allowed the waters of the Atlantic to penetrate Western France a little farther than Blois; but the central and eastern parts did not participate in this subsidence, and evidently remained in the condition of dry land, even the lakes disappearing, so that no record of this part of Miocene time remains in the Paris basin, and merely a few scattered fluviatile and lacustrine deposits in the eastern part of the central area.

The limestone of la Beauce consists of two bands or zones of limestone, each about 60 feet thick, separated by beds of clay and sand, the whole being about 140 feet. It occupies a considerable area from Paris southward to the valley of the Loire, and was evidently formed in a large lake, which seems to have been connected by a river with another lake in the Limagne and Allier districts.

In the Orleanais and Sologne districts the upper limestone is covered by coarse sands derived from the erosion and detrition of the granitic area of Central France, and they contain bones of terrestrial animals.

In the lower part of the valley of the Loire the Lower Miocene (Burdigalian) sands pass beneath a marine deposit, which is known as the Faluns of Touraine, formed in a gulf which extended inland from the Atlantic. A little later the sea spread over Anjou and round the eastern side of Brittany into the area of the English Channel, leaving calcareous sands formed largely of the remains of Bryozoa and calcareous algæ, such as *Lithothamnion* ; but no trace of such beds has been found in the valley of the Seine. The Upper Miocene consists of fine sands without Bryozoa but with marine shells (*Cardita striatissima*, *Nassa prismatica*), and these reach still farther north and east, crossing the Cotentin peninsula by Gourbesville and Carentan.

In Belgium the Miocene is but poorly represented by sandy deposits, and these do not form a consecutive series, the oldest occurring in the Bolderberg near Hasselt, and the newer near Antwerp. The former (Bolderian) appear to be of Lower Miocene age, their lower part containing some Aquitanian species and the higher part yielding *Melongela cornuta* and *Potamides lignitarum*, species which occur in the Vienna basin, in Italy (Langhien), and in Aquitaine. The beds near Antwerp seem to belong entirely to the Upper Miocene, so that there is probably a gap between the deposits of the two localities, for of the Bolderian sands only 22 feet are seen, their summit having been removed by erosion.

B. *Miocene Geography*

From the preceding account of the scanty Miocene deposits which occur in the areas surrounding the British Isles it will be gathered that, during the earlier part of Miocene time, the whole of the British region and of Northern France was in the condition of dry land, the only water spaces being lakes of greater or less extent. This land was the western portion of a continent which included nearly the whole of Northern Europe and probably most of Northern Asia.

One of the geographical puzzles of Miocene time is the manner in which the Bolderian gulf of Belgium was connected with the larger seas on the borders of this continent. It was formerly supposed that there was a southerly communication with the Miocene sea of Switzerland by way of Cologne and the valley of the Rhine,[1] but the later view adopted by De Lapparent is that the Bolderian sea opened northward through the area of the North Sea into the Arctic Ocean.

The chief objection to this latter theory is the southern character of the Bolderberg fauna and the very identity of the species with those of the Southern Miocene. It is difficult if not impossible to believe that such tropical genera as *Melongela* and *Conus* could have been introduced by means of a sea which opened to the north of Scotland. The connection of the Oligocene sea

[1] See De Lapparent's *Traité de Géologie*, Ed. 2, p. 1190.

of Belgium and Northern Germany seems to have been southward by way of Cassel, and it is possible that this may have persisted till Miocene time, and that all traces of the early Miocene deposits were destroyed by the subsequent uplift of the Germanic region into an area of lakes and swamps, wherein the lignitic series was formed.

With regard to the area of the North Sea the northern portion of it was probably raised into land during Upper Eocene and Oligocene times, and if the uplift continued into Miocene time, as seems most likely, it would then have been raised still higher above sea-level. If indeed the submarine Atlantic declivity indicates the position of the western coast-line of Europe in Palæogene time, the similar declivity from the shallows of the North Sea to depths of over 500 fathoms north of the Shetland Isles may be taken as indicating the contemporaneous shore-line in that direction.

All are agreed that large continental areas of land existed in Miocene time around the North Polar region, forming a more or less continuous girdle across Canada, Greenland, Iceland, Northern Europe, and Asia. Consequently I am inclined to take the view that during the early part of the Miocene epoch the British region was not only united with Iceland and Greenland on the north, but was also broadly connected with Norway by a plain of Chalk which probably bore some Lower Eocene deposits on its surface. Southward, England was doubtless united to France across the whole extent of the English Channel.

The next question which presents itself for consideration is that of the surface changes and physical disturbances which took place in the ensuing middle and later parts of the period, and the extent to which the British region participated in them. It is well known that the final movements along the old Armorican lines of flexure in the south of England and the north-east of France occurred sometime in the interval between the close of the Oligocene and the middle of the Pliocene epoch ; and it is generally supposed that they were accomplished in Miocene time.

It must be remembered, however, that the Older Pliocene or Diestian Sands rise on the north side of the Wealden area to heights of about 600 feet above the sea, and to about 500 feet near Calais, from which it must be inferred that the final uplift of the Wealden area was of Pliocene date. It thus becomes a question whether the chief movements in the south of England took place in Miocene or Pliocene time.

So far as the Weald is concerned it seems possible to make an approximate calculation of the amount of material removed from one of the central axes before it was planed off by the Diestian sea; and we can also estimate the height to which that sea-floor must have been raised in Pliocene time. The floor of the early Pliocene sea must have passed over the highest part of the Isle of Sheppey, and may be supposed to have passed over the channel between it and the mainland at about a level of 300 feet (see Fig. 67). Thence it rises to 600 on the Chalk Downs in a distance of 9 miles. From the Lenham outlier to Benenden on the line of the Ticehurst anticline is 16 miles, and if the same rate of rise was continued it would take the plane through another 530 feet, so that over Benenden it would have risen to 600 + 530 feet, *i.e.* 1130 feet. Let us next see on to what formation it must have passed at that level.

The Ticehurst anticline is now let down in a faulted trough,[1] but this faulting is probably due to settlement during the Pliocene uplift. At Hempstead Park, north of the northern fault, the ground is about 450 feet above sea-level, and if we restore the faulted area to its original level, the Tunbridge Wells Sand, which is the surface stratum, would have risen to about 560 feet over the axis of the anticline. The overlying beds would include about 50 feet more of this sand and about 600 feet of Weald Clay. To build up the country to a height of 1130 feet from one of 560 feet, the thickness required is 570 feet, which would not take us to the top of the Weald Clay. Hence we may assume that the floor of the Diestian sea here rested on the upper part of the Weald Clay.

Let us now endeavour to estimate the thickness of beds removed from the same district between the end of Oligocene time, when the land rose above sea-level, and the close of Diestian time, when it had been cut down to the Wealden Clay. In Chapter XII. we found reason to think that both Oligocene and Upper Eocene deposits extended over the eastern part of the Wealden area, so that these were periods of addition to the sedimentary cover, not of erosion and destruction. The Chalk, however, had suffered some erosion locally in earlier Eocene time, for north of Lenham there cannot be more than 400 feet of Upper Chalk, though in Sussex there is nearly 700 feet. Over the Ticehurst area we may reckon its thickness to have been about 500 feet, with 400 of Middle and Lower Chalk below, and consequently the beds removed from this area above the Weald Clay may be estimated as follows:—

[1] See "Geology of the Weald," by W. Topley, *Mem. Geol. Survey*, p. 222.

	Feet.
Oligocene deposits	about 400
Barton and Bracklesham Beds	,, 300
Bagshot Sands	,, 150
London Clay and Reading Beds	,, 400
Chalk (Upper, Middle, and Lower)	900
Gault (=Selbornian).	180
Vectian Beds	300
	2630

To this amount some 80 feet of Weald Clay should be added, making in round numbers a total of 2700 feet. Some of this was doubtless removed by detritive agencies during the earlier part of Miocene time, and a certain amount must be credited to marine erosion during submergence beneath the Pliocene sea; but the greater part was probably removed during the uplifts and during the still later portion of Miocene time before the Diestian subsidence. The Diestian episode seems to have been accomplished in a comparatively short time, so that the thickness removed by the sea was probably not great. Let us credit it with removing 200 feet from the subsiding surface, and neglect the effect of emergence which would be spent on the Diestian deposits themselves. This leaves us with 2500 feet for the thickness removed in Miocene time, an amount which certainly includes a considerable vertical uplift leading to very active detrition. We may perhaps suppose that this detrition accounted for 2000 feet of material.

We calculated the post-Diestian uplift raised the floor of the early Pliocene sea to a height of 1130 feet above present sea-level; the present height of the ground near Benenden is 150 feet, consequently the amount of material removed from this axis since early Pliocene time is about 1000 feet, as compared with a previous removal of 2000 feet. Whatever may be thought of this line of argument, it certainly tends to confirm the prevalent view that the principal disturbance and flexuring of the Wealden area took place in Miocene times; but we may also infer that the Pliocene uplift was considerable, and to it may be ascribed the broad arching of the Weald, as well as many of the faults.

The lines along which the principal flexures were produced have been indicated in Chapter VIII., where the original Armorican flexures were described, and the reader is referred to the map (Fig. 29). In this place it is only necessary to give a more particular account of the flexures themselves.

In the first place, it is clear that the pressure which caused them came from the south. Many of the folds are pushed over so as to be very steep on the northern side, with a much more gentle inclination of the southern side. This is well exemplified in what is often called the monoclinal fold of the Isle of Wight (see Fig. 62), in the northern limb of which the beds are brought into a nearly vertical position. The Vale of Wardour has a similar structure, the beds pitching very steeply on the northern side, while on the southern they are inclined at quite a low angle. The same is the case in several areas along the most northerly axis, *i.e.* near Wootton Rivers in the Vale of Pewsey, in that of Kingsclere, and below the ridge of the Chalk near Guildford, which is known as the Hog's Back.

The compressive force to which the strata of this part of England were subjected is well illustrated by the phenomena which are exhibited in the cliffs of the Dorset coast; more especially in the curved beds of Chalk and the thrust fault of Ballard Head, and in the contorted Purbeck Beds of Stair Hole, near Lulworth. Fig. 63 is a view of the latter, for which I am indebted to Mr. R. F. Gwinnell.

These proofs of the compressive force having come from the south are the more interesting and important, because it is known that the movements which inaugurated the production of the Alps and Pyrenees took place in Miocene time, and that the pressures came from the south. It is therefore somewhat surprising to find that there was no fresh folding along Armorican lines in Brittany, nor to any great extent in Normandy, though the Carentan depression may have been accentuated at this time. It is not till we come to the Pays de Bray that we reach a strong flexure of

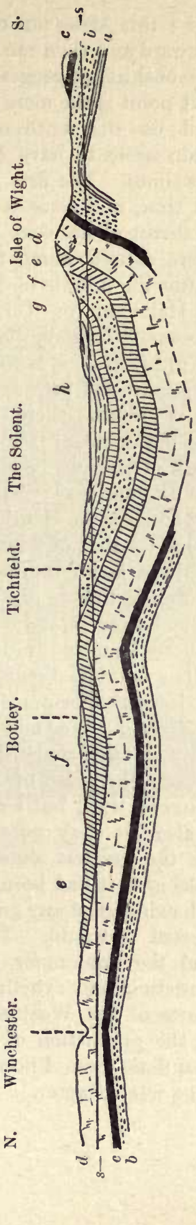


Fig. 62.—Section across Hampshire and the Isle of Wight. Distance about 35 miles.

h. Oligocene Beds. *e.* Lower Eocene. *b.* Vectian Sands.
g. Barton Beds. *d.* Chalk. *a.* Wealden Beds.
f. Bracklesham Beds. *c.* Selbornian. *ss.* Sea-level.

Miocene age ; this passes out to sea at Dieppe, and in all probability curved westward and then ran along the central line of the Channel towards Devonshire, as suggested on p. 187.

The next point is the more precise date at which the compressive forces acted on the south of England. The formation of the Alpine chain seems to have been accomplished by two movements at different times. The first was apparently at the very beginning of Miocene time, and consisted in such powerful thrusts from the south that thrust-planes were formed and the severed slices or sheets of rock were carried along them for many miles. The second occurred after the middle of Miocene time, after the epoch known as Upper Helvetian or Tortonian, and before the Sarmatian, or Upper Miocene. It is supposed that the main flexures of the Alps and their uplift into a mountain range were produced by this second propagation of pressure from the south.

In the Pyrenees there is similar evidence of the earlier movement, but none of the second ; in the Jura, however, the second epoch of pressure is shown by the inclusion of the Miocene Molasse in the flexures. Thus, on the whole, analogy from the dates of flexuring in Southern Europe suggests a late date in Miocene time for that of Southern England.

Again, there is no indication of any great crust-movement in Northern France during the earlier parts of Miocene time. The lakes of the Lower Miocene indicate a period of quiescence, and the deposits in Touraine and Anjou prove only a gentle subsidence ; but there is a notable absence of Upper Miocene deposits, either of marine or lacustrine origin, in the north-central and north-eastern parts of France. We may therefore appeal to these facts as confirmatory of the conclusion above reached, that the flexures which traverse the south of England were formed during the later part of Miocene time, but long before the end of that period.

Here also we may note that the area which has certainly undergone the greatest amount of detrition and denudation, and which looks as if it had been raised to the greatest elevation, does not furnish evidence of any great amount of compression, as we might have expected it would. This area is the large pericline of the Weald and the Boulonnais, where most of the flexures are of the normal anticlinal and synclinal form, especially in the central and eastern parts of the Wealden area. From this I think we may infer that the production of the general broad periclinal structure of the area dates from Pliocene time, and this point will be dealt with in the next chapter.

Photo *R. F. Gwinnell.*

Fig. 63.—VIEW OF STAIR HOLE, NEAR LULWORTH, SHOWING THE MIOCENE FLEXURING OF PURBECK BEDS.

C. *Land-Sculpture and Valley-Formation*

In discussing the general geography of Miocene time, and in describing the remarkable compression and uplift of Southern England, we have only paid attention to a small part of the British region, and we must now consider what aspect the other and much larger parts presented at this epoch, and what modifications they may have undergone.

We have supposed that the northern part of the region still maintained the high level above the sea to which it had risen in Eocene and Oligocene times, modified only by the subsidence of the Hebridean trough and the depression of the Irish Sea and St. George's Channel, which had become broad plains occupied by a great river and its tributaries. All the bolder physical features of the British Isles were now in existence, but some of them were comparatively new and must have exhibited a very different aspect from that which they wear at the present day. The most important of these new features were: (1) the dome of the Lake District; (2) the long Pennine anticlinal ridge; (3) the oval uplift of the Midlands.

The thick cover of Cretaceous sediments which originally overspread all these areas had doubtless been removed during the lapse of Oligocene time, and the river-courses which had been determined by the original slopes and inequalities of the surface must have been fairly well established by the beginning of Miocene time. The work of valley-formation and scarp-development would be actively continued during Miocene time, and there can be no doubt that a large amount of land-sculpture was accomplished in this period; but I think there has been a tendency to crowd too many events into the Miocene epoch, and to credit it with a larger share in the making of the present surface than it really had.

Much erosive and sculpturing work had been done before it began, and much was also done in the succeeding Pliocene epoch, but it will be convenient here to indicate briefly some of the special features which must have been developed in England during the course of all three epochs.

1. The Lake District.—The structure and history of the Lake District has been fully described by Dr. Marr,[1] and illustrated by the map which he allows me to reproduce in Fig. 64. This map shows the areas occupied by the principal geological formations as now exposed, but Dr. Marr supposes that these were covered by a mantle of Jurassic and Cretaceous deposits, and that it was on

[1] Pres. Address, *Quart. Journ. Geol. Soc.* vol. lxii. p. lxxxiv (1906).

the surface of the Chalk that the river system was initiated. The radial character of this system is indicated on the map by the position of the chief lakes, which are shown in black; but these

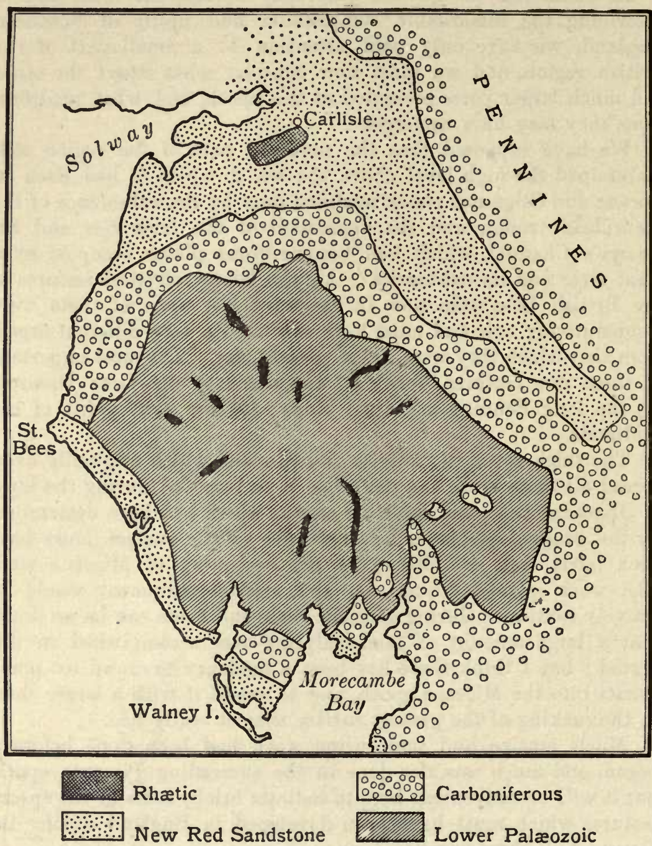


Fig. 64.—SKETCH MAP OF THE LAKE DISTRICT (J. E. Marr).

only mark out the lines of some of the valleys, for there are others in which no lakes occur.

Dr. Marr shows that the uplift which gave rise to the mountains of the Lake District did not produce a simple symmetrical dome, but one main dome of elliptical form, or a shape like a spoon with a short handle, and perhaps a minor dome in the Skiddaw district.

The principal watershed is that of the Scawfell district, where no less than seven important valleys have their sources within two or three miles of Scawfell mountain ; these are : (1) the Langdale-Windermere valley ; (2) the Duddon valley, running a little west of south ; (3) Eskdale, running S.W. ; (4) Wastdale, running nearly parallel to Eskdale ; (5) Ennerdale, going west ; (6) the Buttermere valley ; (7) the Derwent, which runs northward. The handle of the spoon lies to the eastward, along a watershed connecting Scawfell with the Shap Fell. On the northern side of this ridge are the Thirlmere, the Ullswater, and the Haweswater valleys, while on the southern side are those of Troutbeck, Kentmere, and Sleddale. For further details the reader is referred to Dr. Marr's Address.

The subsidiary uplift of the Skiddaw district also shows a radial arrangement of streams on a smaller scale, and it is in this area that olivine rocks like those of Tertiary age are found.

2. The Pennine Ridge.—If the date of the formation of this great anticline has been correctly fixed in Chapter XIII., its original surface would consist of Chalk spreading in a broad arch over the rising ridge. Of the rain falling on this some would run off its flanks, forming valleys partly by erosion and partly by solution, while much would sink in springs, carrying away Chalk in solution. We may assume that the Pennine Chalk was similar to that of Yorkshire, which is more or less hard throughout, and consequently does not tend to form successive escarpments like those of Cambridgeshire and Hertfordshire. The earliest system of valleys would be those of transverse (consequent) streams, with branches which tended to meet and interlace over the water-parting, like those of the Chalk Wolds of Yorkshire. These valleys would gradually be deepened till some of those near the watershed cut down into the underlying Jurassic rocks.

Where these underlying rocks were either clays or sandstones, disintegration and removal of material would proceed more rapidly, and two lines of Chalk escarpment would begin to appear along some of the more central longitudinal valleys. These valleys would be gradually widened till Chalk-escarpments were formed along each flank of the ridge, and the axial river-courses would be transferred to the Jurassic rocks, and thence to the Keuper marls.

There must have been a time when the range consisted of an axial tract of Keuper sandstones, passing both eastward and westward beneath broad plains of Red marl and Lias clay, beyond which were broken escarpments of Jurassic limestones and sandstones, and still farther away more regular escarpment ridges of

Chalk. This stage may have been reached by the middle of the Miocene epoch.

We have already assumed that the Keuper sandstones had overlapped both the Bunter and the Permian Beds toward the central parts of the old worn-down pre-Triassic Pennine axis; consequently, as the Keuper sandstones were removed from this central tract, an irregular surface of Carboniferous rocks would make its appearance, and the drainage system would be transferred to this surface, being eventually modified by its irregularities, and by the varying powers of resistance to erosive agencies possessed by its component rocks.

On the eastern side of the Pennine range the original consequent or dip-flowing streams are still represented by the upper waters of the rivers Tyne, Wear, Tees, Swale, Ure, Wharfe, Aire, Calder, and Don. On the western side there has been much more modification and alteration of the original system of drainage, but the upper tributaries of the Mersey and the Weaver can be recognised as representing two of the original consequent streams.

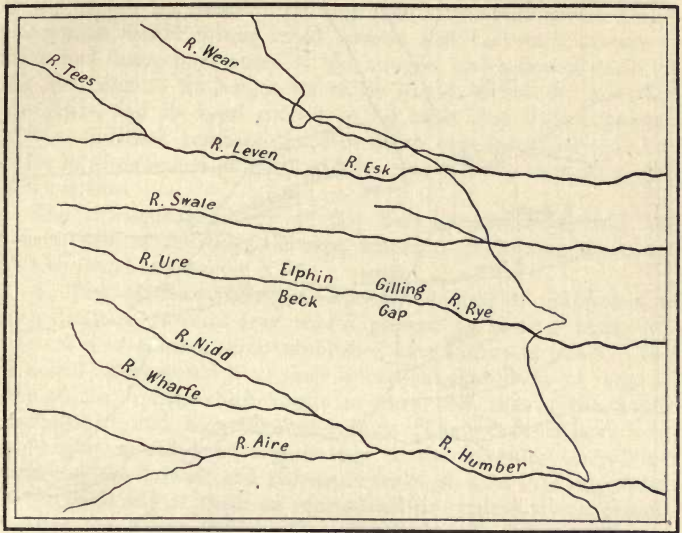
3. North-East Yorkshire.—There is another area which deserves special attention, because it has been surmised that a local uplift took place therein during Miocene time. This is the north-east part of Yorkshire, which embraces the district of the Cleveland Hills. The geological history of this area has been written by Mr. T. R. C. Reed,[1] and his conclusions only require slight verbal alteration to bring them into accord with the general views stated in the preceding pages.

Mr. Reed's first cycle would, in my opinion, date from the uplift of the Pennine range in Oligocene time, and would be exactly what he calls it, "the pre-Miocene cycle." Mr. Reed supposes that the rivers flowing off the Pennine slope originally took fairly straight courses across Yorkshire, and he indicated these on a map which, with his permission, is reproduced in Fig. 65.

There is good reason for regarding the valley of the Esk, which runs eastward to Whitby, as representing a portion of the original valley of the Tees. The Swale and the Ure are shown on the map as independent rivers, but Mr. Reed admits that the Swale may from early times have been only a tributary of the Ure, and I think that this is the more probable supposition. The ancient course of the Ure has been restored on the assumption that the line which it took is indicated by the direction of certain streams and dry valleys which still exist; these are: (1) the Gilling Gap at the west end of the Vale of Pickering, and the little streams which flow from each end of it; (2) a dry valley across the Chalk Wolds near Wintringham.

[1] *Sedgwick Essay* for 1900, published by the Cambridge University Press.

In the Gilling Gap the watershed is not much above 300 feet, and lies within a col or pass between the Hambledon and Howardian Hills. This gap has obviously had a greater extension in one direction or the other, and its position suggests that this was in a westerly direction, and that the Elphin Beck, which now flows west into the Vale of York, is a reversed or obsequent stream developed along the line originally taken by the Ure. At the eastern end of Gilling Gap is Hole Beck, flowing east into the Rye,



Stanford's Geog^l Estab^t. London.

Fig. 65.—MAP OF THE PRE-MIOCENE DRAINAGE OF THE N.E. OF YORKSHIRE (After Mr. T. R. C. Reed.) Cycle 1.

which is now a tributary of the Derwent; but in a line with the course of the Rye is a curious gap in the Chalk escarpment south of Knapton, and this is continued eastward as a dry gravel-strewn valley through the Chalk Wolds, finally leading into a modern valley which opens seaward at Bridlington.

The Humber is the most southerly of the streams discussed by Mr. Reed, and is the only one which has maintained its original course down to the present time. Formed originally by the union of the Nidd, the Wharfe, and the Aire, it ran nearly due east over the Chalk escarpment, and now cuts that escarpment in two. Moreover, by the subsequent development of the Ouse it has captured and diverted the head streams of the Ure and the Swale. The changes introduced by the development of strike-streams along the surface of the Trias toward the close of the first cycle are shown in Mr. Reed's second map (see Fig. 66).

We now come to Miocene time, and Mr. Reed believes that there was an uplift along the older east and west axis of the Cleveland Hills. "The deformation thus produced," he says, "in the surface of the old peneplain, gave rise to a new watershed more or

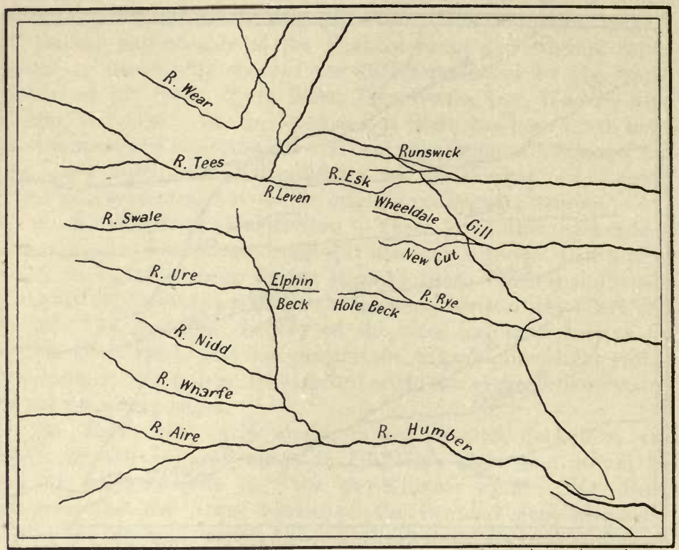


Fig. 66.—MAP OF THE PRE-MIOCENE DRAINAGE OF THE N.E. OF YORKSHIRE (After Mr. T. R. C. Reed.) Cycle 2.

less parallel to the direction of the original consequent streams, and it gave also a southerly dip to the Cretaceous Beds on its southern flanks." From the new watershed thus initiated, a new set of secondary consequent streams was developed, running with the dip of the beds to the north and south. Mr. Reed also agrees with me in thinking that the whole region was elevated at the time of the Miocene uplifts, so that its surface stood much higher than it does now, and higher also than it did in Oligocene time.

He then discusses the history of all the Cleveland streams, and of the gradual excavation of the Vale of Pickering; but, of course, only a portion of this history lies within the Miocene period.

This portion I will briefly summarise :—The descent and growth of the southerly flowing streams from the Moorland watershed would rapidly cause the Chalk escarpment to retreat to the southward. The beheaded Ure (or Rye), reinforced by several of these streams, would quickly cut down to the Kimeridge Clay, "over which it would meander in a slack reach above its entry into the Chalk outcrop."

At the same time a strike-stream flowing east along the same Clay would come into existence in the now destroyed eastern part of the area. Its situation on clay land at the foot of the Chalk escarpment would favour rapid erosion and backward extension, till it had intercepted many of the streams which flowed south off the Moorlands. At length its valley would be reduced to such a low grade, and its head carried so far back, that little separated it from the slack reach of the Ure above mentioned, so that the latter in some season of flood was diverted into the channel of the strike-stream.

The subsequent history of the Vale of Pickering, and the development of the river Derwent, belong to Pleistocene time, and will be found in Chapter XVI.

4. The Midland Area.—The development of the system of river-drainage in this area would proceed on similar lines, the original river-courses being established on a surface of Chalk. The principal rivers would have their sources on the dominant ridge or arch of the uplift, which seems to have been that of the South Staffordshire and East Worcester line. Their courses have been profoundly modified by transference to the irregular underlying surface of the Triassic and Palæozoic rocks, so that it is impossible to recognise any of them as represented by modern rivers, except, perhaps, the Trent and the Tern in the north, and the Kennet and Bristol Avon in the south.

The Tern is a small river, which now runs into the Severn near Worcester, and has eastern tributaries which rise near Newport. It is probable that in Oligocene and Miocene times the main watershed lay over Cannock Chase, and that the primitive Tern was a longer river flowing thence by Newport westward beyond Shrewsbury, to become a tributary of the Upper Severn, which in those times had no connection with the Lower Severn, but was a tributary of the Dee; or perhaps it would be more correct to say that the Dee was a tributary of a nameless river which had its chief source in Central Wales, and flowed northward along the western border of Cheshire.

Inspection of any good map of Staffordshire and Shropshire will show that the Trent, by occupying the old Triassic valley or depression between the Carboniferous rocks of Derby and those of Staffordshire and Warwickshire, has cut its valley down to a lower level than the Tern, and has consequently been able to extend its drainage area westward into the district between Stafford and Newport, which in early times lay probably on the western side of the watershed and supported affluents of the Tern.

The origin of the Kennet and the Bristol Avon has been mentioned on p. 386. Before the Armorican movements of Miocene time and the production of the anticline which runs through the Vales of Pewsey and Kingsclere, there may have been a more irregular drainage system; but after the Miocene uplifts it is clear that the dominant ridge lay over the Pewsey and Kingsclere line, and this must have formed the main watershed of the central part of Southern England. The streams flowing off the southern side of this ridge were the ancestors of the Salisbury Avon, the Test, and the Itchen. The brooks which ran off the steeper northern side of the Pewsey ridge were diverted into the Kennet, and the western Avon, in consequence of the pre-existing north and south watershed, was here truncated by the curve of the Mendip-Pewsey ridge.

The area which is now the English Channel must have been greatly altered by the uplift of Southern England and the N.E. of France; but it is impossible to reconstruct the geography of the eastern part of this area, because of the subsequent subsidence and re-elevation of the Weald and Pas de Calais, for this must have completely effaced the Miocene system of drainage. Of the configuration of the western part of the Channel area, however, we may venture to form some idea, for this was much less modified by the flexures, and its drainage would still naturally be directed into that gulf of the Atlantic which had existed more or less continuously through Eocene and Oligocene times, and which had been reoccupied by the sea of the Middle Miocene.

The great upheaval had doubtless caused the Atlantic to retreat to the western end of this gulf between Cornwall and Brittany, but the depression would be occupied by a river which must have drained all the central part of the Channel area. It is probable also that this river received tributaries from the north along continuations of the valleys of the Exe, the Axe, the Avon, and the Test.

The history of the rivers of Devonshire has not yet been written, but suggestions have been made with regard to some of them, and Mr. Clayden has attempted a restoration of the courses of the Devonshire streams in Eocene and Oligocene times.[1] I agree with

[1] See his *History of Devonshire Scenery*, p. 169.

him in thinking that in those periods the general slope of the country was toward the east, and that the direction of the modern rivers is largely due to the southern slope imparted to the country by the subsequent Miocene uplift. This naturally produced important alterations in the whole system of drainage ; tributaries flowing southward were given increased powers of erosion and backward extension, with the result that they captured streams flowing eastward to the north of them. It was probably in this manner that the Dart, the Teign, and the Exe were diverted from former courses and made to take a southerly or south-easterly direction.

With regard to the Avon, which reaches the sea near Christchurch, the fact that its mouth is opposite the middle of the wide gap between the Isle of Purbeck and the Isle of Wight is to my mind very suggestive. There must have been good reason for the existence of such a break in the great Purbeck anticline, and for the entry of the sea into the Hampshire basin at this place ; such a cause is found in the supposition that the valley of the Avon was originally continued across the Purbeck monocline. The crossing of this axis was probably effected at the intersection of two local periclines or synclines, just as the Winchester axis is crossed by this same river in a depression between two such local flexures. The Test and the Itchen may have united their waters and have formed a river which flowed south-westward across the New Forest, joining the Avon before it passed through the gap in the Purbeck monocline.

CHAPTER XV

PLIOCENE TIME

A. *Stratigraphical Evidence*

The Pliocene deposits which enter into the structure of England are only found in the counties of Kent, Essex, Suffolk, Norfolk, and Cornwall. Those of the eastern counties have been subdivided into a succession of groups and still smaller units or zones, and Mr. F. W. Harmer has recently given special names to the latter. As, however, I did not adopt these in my volume on *Stratigraphical Geology*, but used the older names and the more simple arrangement of dividing the whole series into Lower, Middle, and Upper Stages, the same grouping will be used here. These divisions, and their equivalents in Belgium and Holland, are as follows:—

Stages.	England.	Belgium and Holland.
Upper	Cromer Beds Weybourn Crag Chillesford Beds Norwich Crag	not represented.
Middle	Red Crag	Amstelian.
	Walton Crag	Scaldisian.
Lower	Coralline Crag	Casterlian.
	Lenham Beds	Diestian.

1. Lower Pliocene.—The oldest deposits of Pliocene age in England are certain deposits of ferruginous, but originally glauconitic, sand, which at Lenham and other places along the Chalk Downs of Kent are near or somewhat above the level of 600 feet.

The sands often contain flint pebbles, and include layers of loamy clay and seams of fossiliferous ironstone, and though their aspect is not that of deep-water deposits, yet the perfect and unworn condition of the shells shows that they are not shore deposits, and the fauna seems to indicate a depth of about 40 fathoms.

The Lenham Sands occur at intervals along the Downs from the heights above Folkestone to Maidstone, and somewhat similar sands occur at Chipstead, near Croydon, but though they are now only found along this narrow tract, it is evident that they are the remnants of a formation which was once spread far to the north, and also some distance to the south of this line.

It is clear, in fact, that when these sands were deposited the summit ridge of the North Downs was a sea-floor, and lay below water of some depth, and that to restore the surface of this early Pliocene sea-floor we must imagine it as stretching southward from a certain height above the Isle of Sheppey, over the North Downs and across much, if not the whole, of the Wealden area. Fig. 67 is a section across the Lenham Downs, and the line *vv* shows the position of a portion of this old sea-floor; but the figure is only a diagram, and the Lenham Beds do not lie exactly on the summit of the escarpment, but a little below it on the northern side. Hence the basal plane of these beds does not truncate the ridge, but passed over and beyond it, and rose to still higher levels farther south.

From the position of the Lenham Beds on the North Downs we may draw three important conclusions : (1) that a great thickness of Eocene, Chalk, etc. had been previously removed; (2) that in early Pliocene time the area sank below the sea ; (3) that a subsequent upheaval raised

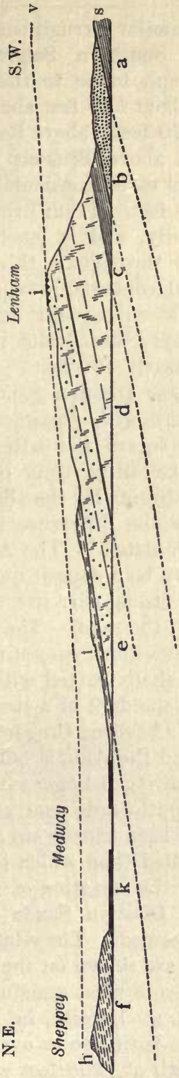


Fig. 67.—Section through the Isle of Sheppey and the North Downs, near Lenham.

(Horizontal distance about 18 miles. Vertical scale about 1700 feet to an inch.)

k. Alluvium. *f.* Eocene deposits. *c.* Gault.
i. Lenham Beds. *e.* Upper Chalk. *b.* Vectian Sands.
h. Bagshot Sand. *d.* Middle and Lower Chalk. *a.* Weald Clay.
vv. Basal plane of the Lenham Beds *ss.* Present sea-level.

a sloping plain out of which the existing physical features have been carved.

Outliers of similar ferruginous sands occur also at intervals near Calais and in Southern Belgium, the level of their base-line sinking lower and lower to the eastward. Thus, at Cape Blanc-Nez they are about 500 feet above the sea ; at Cassel, near Ypres, their level is 470 feet ; above Renaix it is 445 ; at Gramont, 380 ; on the heights above Brussels it is only 245 ; and near Diest, though the level varies considerably, their base nowhere rises above a height of 200 feet. From Brussels northward the base-line sinks still more rapidly, and is less than 20 feet above the sea near Antwerp. Yet throughout this range the sands are similar in constitution and contents, proving that the present differences of level are due to subsequent differential movement of the land. Around Diest and Tessenderloo they cover a large area, and attain a thickness of nearly 100 feet.

Formerly these Diestian Sands were believed to pass into the sands of Antwerp with *Isocardia cor* (Casterlian), but the Belgian geologists now regard the latter as a newer zone. Mr. Harmer correlates the Coralline Crag of Suffolk with the Casterlian of Belgium, and accounts for the slight differences in the faunas of the two deposits by the difference in the conditions under which the beds were accumulated.[1] The Antwerp Beds consist of fine sand which appears to be a deposit quietly accumulated on a sea-bottom undisturbed by strong currents, so that bivalve shells remain with united valves in the sand. The Coralline Crag, on the other hand, is a Bryozoan limestone, consisting mainly of fragments of Bryozoa and Molluscan shells mixed with a little fine sand, and evidently accumulated in the drift of a strong current.

The tract of Coralline Crag now remaining between the estuaries of the Deben and the Alde is only a remnant of a formation which was originally of much larger extent, but its extension was certainly more to the southwards and eastwards than to the north. It appears to have been broken up and in great measure destroyed by the sea of the Red Crag which is bedded round it, this destruction being aided by the elevation of the southern part of the sea-floor over which the Diestian Sands (Lenham Beds) and the Coralline Crag had been formed. The relative areas occupied by the Coralline and Red Crags are shown on the map (Fig. 68).

The thickness of what remains of the Coralline Crag is from 60 to 70 feet, but at Utrecht, in Holland, the corresponding sands were found in a boring to be over 300 feet thick, this boring being carried to a depth of 1208 feet without reaching the base of them.

[1] *Quart. Journ. Geol. Soc.* vol. liv. p. 346.

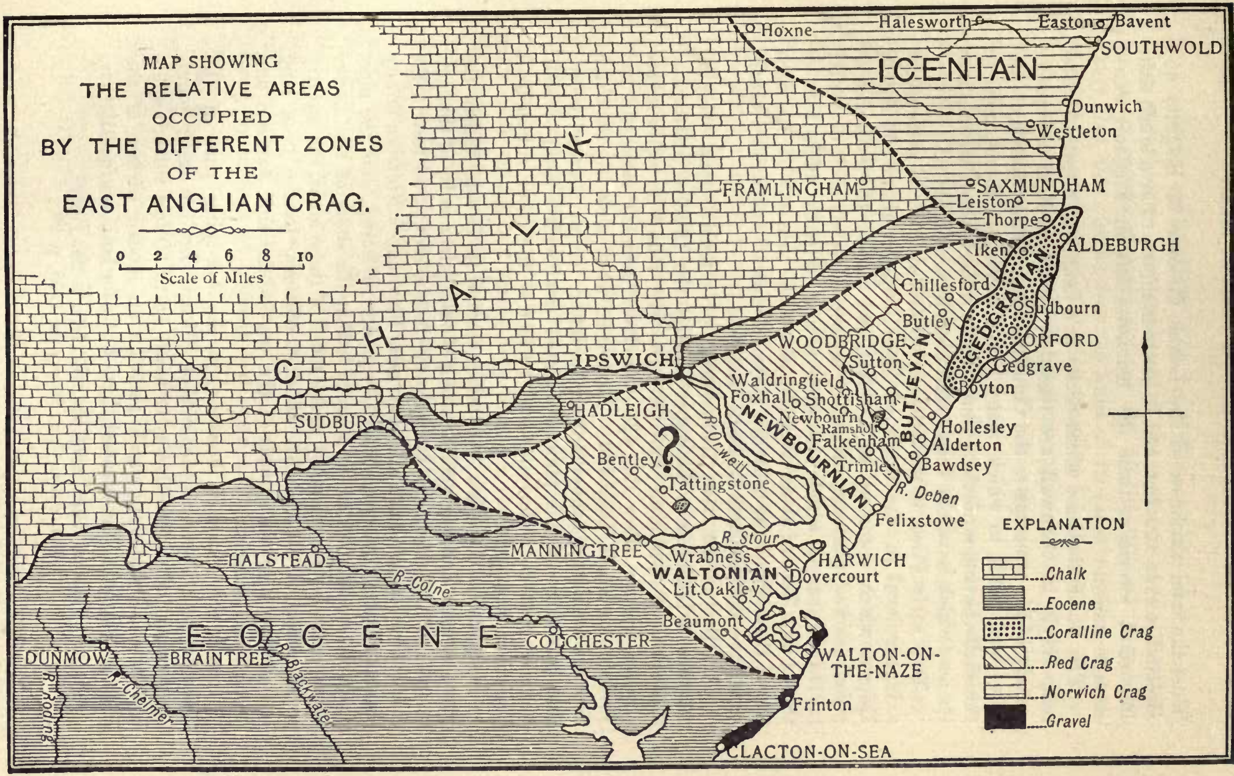


Fig. 68.—MAP SHOWING THE RELATIVE AREAS OCCUPIED BY THE DIFFERENT ZONES OF THE EAST ANGLIAN CRAG. (Reproduced by permission of Mr. Harmer and the Council of the Geological Society.)

Thus the total thickness of the Lower Pliocene in Belgium and Holland is over 400 feet, and it has been shown to be a much more important formation than the remnants left in England would seem to indicate.

The St. Erth Beds, which occur at a height of about 100 feet near Hayle in Cornwall, are regarded by Mr. C. Reid as approximately of the same age as the Coralline Crag. They consist of fine clays and sands, in which many fossils have been found, none of the shells having a northern range, while some of them are southern species, which have not been found elsewhere in Britain.

This early Pliocene sea has also left evidence of its presence at a higher level in the shape of beach deposits round St. Agnes' Beacon, which occur up to 375 feet, and also in the existence of a well-marked platform, backed by a steep slope, which is evidently an old sea-margin which was often a line of cliffs. The foot of this is at a level of about 430 feet above the sea, and it has been traced throughout the southern part of Cornwall and more recently round the Bodmin and Boscastle districts.

Mr. Barrow mentions the existence of extensive gently-sloping marshes or boglands at the upper edge of the 430-feet platform to the south of Bodmin,[1] and Mr. Dewey[2] found a well-marked plateau feature below the 430-feet level between Boscastle and Treligga in North Cornwall. Moreover, what seem to be beach deposits are actually preserved on the latter, for Mr. Dewey records that pits dug on this plateau exposed sand with a seam of well-rounded pebbles, underlying 8 or 10 feet of the local rubble-drift known as Head.

No such platform has yet been observed in Devon, unless the plateaus near Torquay and Brixham should prove to be of this age, in spite of their being at much lower levels, about 300 feet in the case of Babbacombe and only 220 near Brixham. No trace of any coastal platform occurs in East Devon nor in Dorset, and the most probable explanation of its absence is that the shore of the Lower Pliocene sea lay considerably to the south of those areas, the easterly continuation of the Cornish 430-feet platform having been long ago destroyed by the inroads of the sea on the soft Jurassic and Cretaceous deposits.

Across the Channel, however, in the low-lying part of the Cotentin, near Carentan, deposits of Pliocene age are again found. They consist of a greenish clay or marl, 18 to 20 feet thick, underlain by a conglomerate which rests on an eroded surface of the Miocene faluns. The fauna of these beds, for both are fossiliferous,

[1] *Quart. Journ. Geol. Soc.* vol. lxiv. p. 385 (1908).

[2] *Sum. Prog. Geol. Survey* for 1908, p. 29.

is considered by Mr. C. Reid to be of the same age as that of St. Erth, and thus we have evidence of the extension of the Pliocene sea as far east as the longitude of the Isle of Wight. It is not likely that this district was the limit of its eastern extension, but no other traces of it have yet been found in Normandy, and if any such further extension existed we must suppose that it lay wholly within the area now occupied by the waters of the English Channel.

2. Middle Pliocene.—In this division I include all the subdivisions of the Red Crag in Essex and Suffolk, namely those of the Walton, Beaumont, Newbourn, and Butley districts. Of these zonal areas (see map, Fig. 68), and of their manner of formation, Mr. Harmer writes as follows in his latest publication:[1] "As no crag beds of Newbournian type overlie the Walton Crag, nor does any Butleyan Crag rest on the Newbournian, it would seem that the tectonic movement of upheaval and subsidence gradually laid dry the southern part of the Crag area, submerging at the same time the country farther to the north; a series of shallow bays or inlets thus came into existence along the western coast of the North Sea, as the earlier ones were silted up by shelly sand, and the slight alterations of level proceeded, each situated successively somewhat farther to the north or north-east."

"Instances of such silting up in recent times may be observed in Holland." . . . "As I have pointed out elsewhere, the coasts of Holland are covered by masses of dead shells driven against them by the gales from the south-west now prevalent in that region. As such drift occurs but rarely at present on the shores of Suffolk, its accumulation there in such abundance during the Crag period indicates, I think, that the strongest gales were then from the east, the storm-tracks lying at that time farther to the south."[2]

These beds of Red Crag must originally have extended farther north, or at any rate north-east, but they appear to be quite cut out by the Norwich Crag, the base of which lies at a lower level than that of the Red Crag. The thickness of the latter is not more than 20 or 30 feet in any one area, but in Holland the corresponding portion of the Pliocene series (Scaldisian and Amstelian), as proved by borings at Utrecht and Amsterdam, is about 600 feet thick.

3. Upper Pliocene.—As shown in the map (Fig. 68), the Norwich Crag and the other deposits of this group occupy a separate and more northern area. Moreover, this crag abruptly truncates

[1] "Geology in the Field," *Geol. Assoc.*, 1909: "Pliocene Deposits," p. 96.

[2] "The Influence of the Winds upon Climate," *Quart. Journ. Geol. Soc.* vol. lvii. (1901) p. 407.

both the Red and the Coralline Crags, and is banked up against them, its base lying on the London Clay, and its thickness at Southwold, only 12 miles north of Aldeburgh, being 147 feet.

The Norwich Crag was evidently formed under different physical and climatic conditions from those which had previously prevailed; the sea must have been more widely open to the north, for most of the characteristic shells of the Red Crag are absent, and there is a larger number of such recent species as now live on our eastern and northern coasts, including such forms as *Astarte borealis.* Mr. Harmer believes that this crag was formed on the western side of the estuary of the Rhine, and that the Chillesford Clay, which overlies both the Red and Norwich Crags, actually represents a branch of the Rhine. It certainly marks the channel of a large river, for the mapping of this particular deposit shows it to have the sinuous course represented in the map (Fig. 69).

As regards the Weybourn Crag, of which only a small area remains, it may be the deposit of the open bay into which the Chillesford river opened, or it may mark an encroachment of the sea upon this portion of the Rhine delta at a slightly later point of time.

The highest beds included in the Pliocene series are the Cromer Beds, consisting mainly of the so-called "Forest Bed," which, however, is only a band of clay and lignite containing drifted stumps and branches of trees, not the remains of a submerged forest, as formerly supposed. The beds are really a variable group of sands, gravels, clays, and lignite, from 10 to 20 feet thick, and appear to have formed part of an alluvial flat connected with the delta of the Rhine. The gravel may, in fact, be regarded as Rhine valley-gravel, for the pebbles of which it consists have been carefully studied by Mr. Reid, who found them to be chiefly of flints, light-coloured quartzites, vein quartz, and hard grits, with other stones which seem to have been derived from Carboniferous, Lower Cretaceous, and Eocene rocks. There is a total absence of Jurassic débris and of the liver-coloured quartzites which are so common in the English Trias. "In fact," to quote Mr. Reid,[1] "if the river had flowed from the south, west, or north, it must have brought a quite different collection of stones. From the north-east [had it come from that direction] it would probably flow entirely over Chalk. It therefore seems that only from the south-east and east could the stones be derived." This conclusion, as will be seen in the sequel, is an important factor in the restoration of the physical geography of the North Sea area at this particular time.

Near Cromer these terrestrial deposits are succeeded by the

[1] "Geology of Country around Cromer," *Mem. Geol. Survey*, p. 56.

Leda myalis bed, which is from 4 to 15 feet thick, and consists of fine loamy sand with marine shells, some of them lying undisturbed

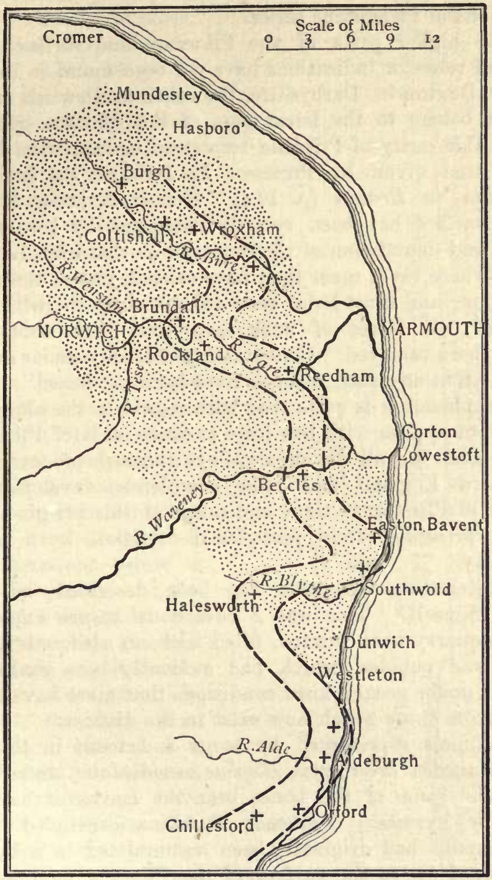


Fig. 69.—MAP SHOWING THE PROBABLE COURSE OF THE ESTUARY IN WHICH THE CHILLESFORD CLAY WAS DEPOSITED. The places where that clay is found are indicated by the mark +. (Reproduced by permission of the Author and of the Council of the Geological Society.)

in the position of life. It is clear, therefore, that the last change which occurred in this portion of the Pliocene area was a submergence which brought in the sea once more over the lower parts of the newly-formed land. This deposit represents the time of passage from Pliocene to Pleistocene time, for it is overlain by a bed full of Arctic plants, and consequently it is by some regarded as the base of the Pleistocene series.

Of the higher parts of the Pliocene land-surface only two undoubted relics or indications have yet been found in Britain, the one near Buxton in Derbyshire, the other at Dewlish in Dorset, and both belong to the latest part of the Pliocene epoch. The reason of this rarity of Pliocene terrestrial or lacustrine deposits is probably that given by Professor B. Dawkins in his work on *Early Man in Britain* (p. 144). His explanation is that the Pliocene surface has been entirely destroyed by the subsequent detrition and denudation of the country ; so that even in limestone districts, where caves must then have existed, just as they do at the present time, and must have been inhabited by the wild beasts of the period, all traces of such caves and their contents have generally been removed. Consequently it is only under exceptional conditions that any such remains have been preserved.

This explanation is quite true with regard to the older Pliocene deposits, but applies with less force to those of later Pliocene date, for, as we shall see, all the chief valleys and escarpments of Central and Eastern England had been completely developed at the beginning of Pleistocene time, and much of this pre-glacial surface has been preserved from post-glacial detrition by a mantle of boulder-clay.

One interesting exception has been described by Professor Dawkins himself.[1] This was a cavernous fissure exposed in a limestone quarry near Buxton, filled with an ossiferous deposit of red clay and pebbles, which had evidently been washed in by water, but under geographical conditions that must have been very different from those which now exist in the district.

The animals represented by bones and teeth in this deposit include *Mastodon arvernensis*, *Elephas meridionalis*, and *Rhinoceras etruscus*, and some of the bones bear the marks of having been gnawed by hyænas. Professor Dawkins concluded that the animal remains had originally been accumulated in a hyæna-den, which opened on to the surface of the Pliocene land at a much higher level, and from which passages and swallow-holes led down to lower chambers and fissures, such as that exposed in the quarry at Doveholes.

Professor Dawkins's remarks on the alteration of surface-conditions and the detrition of the district since Pliocene time are so interesting and instructive that I quote them in full,

[1] *Quart. Journ. Geol. Soc.* vol. lix. p. 105 (1903).

together with a copy of the illustrative section constructed by him (Fig. 70). It should first be mentioned, however, that the limestone in which the quarry is opened forms a plateau between 1150 and 1200 feet above the sea, and is now a water-parting or divide between two sets of streams; on the west of it the ground rises in a continuous slope to the Millstone Grit plateau of Black Edge (about 1650 feet above sea-level).

"Under the existing conditions," writes Professor Dawkins, "no water is delivered into the area of the Victory Quarry from the west. Had there been drainage in this direction it would have disappeared in the limestone before it reached the quarry. At the time when the cave was filled, it obviously received the drainage of the rocks which now form the hills, and must, therefore, have been at the bottom of a valley instead of being on a water-parting. I have attempted to restore this ancient land-surface in the dotted lines of the figure (Fig. 70), in which I have carried the lower boundary of the Yoredale Rocks along the plane of dip to a sufficient height to command the cave. If this be taken as an approximation to the

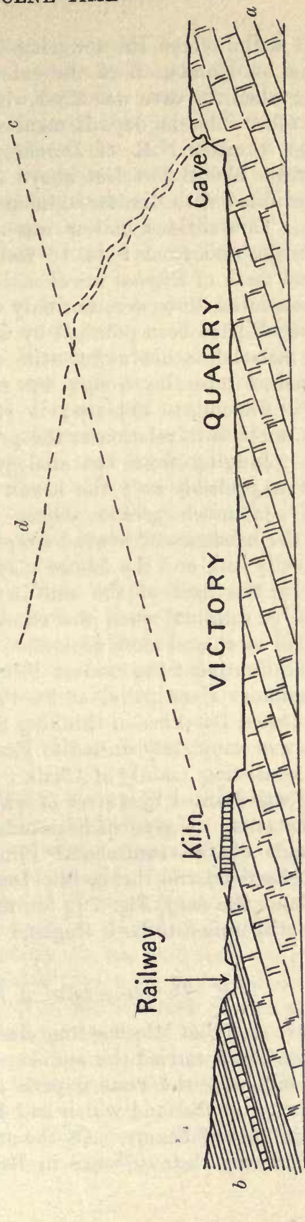


Fig. 70.—Section through the Victory Quarry at Bibbington, near Buxton. Scale 12 inches to a mile. (After Prof. B. Dawkins.)

d. Probable Pliocene surface. *b.* Yoredale Shales.
c. Prolongation of limestone surface. *a.* Carboniferous Limestone.

truth, it will involve the lowering of the general surface of the limestone by denudation to the extent of at least 330 feet since the time when the cave was filled with its present contents."

The other Pliocene deposit mentioned above occurs at Dewlish, a village 6 miles N.E. of Dorchester. Here, on the top of a Chalk ridge about 350 feet above sea-level, was found a trough or fissure filled with fine ferruginous sand and two layers of flint pebbles. This curious hollow was about 100 feet long by only 4 feet wide, and from 8 to 16 feet deep. The sand contained bones and teeth of *Elephas meridionalis* and *El. antiquus*, and many of the associated flints were not only worn but polished, resembling stones which have been polished by wind-blown sand.

The material is not a fluviatile deposit, though it may have been washed into the trough by water, but the origin of the trough is difficult to explain; it runs from N.N.W. to S.S.E., and has no definite relation to the present physical features of the country. Judging from the analogy of the Derbyshire cave, I think it is probably only the lowest part of a fissure which was originally of much greater depth. The sand-polished stones suggest the existence of a wind-swept plateau with a dry, sandy, and gravelly soil, and the fissure may possibly have been a crack formed by the heat of the sun in a dry climate, subsequently widened by solution when the climate became more moist and the rainfall more and more copious.

On the Continent the nearest Pliocene deposit of the same age is an ossiferous river-gravel at St. Prest, near Chartres. I agree with Professor Dawkins in thinking that in Upper Pliocene time England was completely united to France by a tract of undulating country, consisting mainly of Chalk; and that the greater part of this tract was drained by a river of which the Seine and the Somme were tributaries. Under such circumstances it would be easy for the animals of the continental Pliocene fauna to migrate into Southern England and thence into Derbyshire, as well as westward into Ireland (see map, Fig. 72), for, as he points out, Ireland was probably still united to both England and Scotland.

B. *The Geography of Pliocene Time*

We have seen that Miocene time closed with a general subsidence, which once more carried the sea over parts of the Miocene land; and not only over the western parts adjacent to the Atlantic, but over a portion of the land which had been ridged up along the old Armorican lines of flexure. Of the great extent of this submergence we find very clear evidence in Belgium and France, for there the Diestian Sands not only overstep the Miocene deposits but pass westward over the Eocene on to the Chalk near Calais and on to the heights above Folkestone. Moreover, their character at these places is not that of littoral deposits, but of one formed below water of some depth—about 40 fathoms, according to Mr. Reid. Consequently it is clear that the shore-line of this Diestian sea must have lain at a considerable distance to the south-west of the Chalk Downs at Calais and Dover; and there is no reason why this sea should not have extended indefinitely in that direction.

It is true that no remnants of Diestian deposits have been found on the south side of the Boulonnais, nor on the Chalk Downs of Sussex, and their absence has been regarded as evidence that the eastern and western Pliocene seas were separated by an isthmus of land across the Straits of Dover; but negative evidence is proverbially unsafe, and the absence of such deposits can be accounted for in several ways. It may be that on this side the Pliocene Sands lay on Eocene Beds, and have been destroyed with the latter; or again it may be that the southern side of the Wealden uplift was subsequently raised rather higher than the northern, and consequently exposed to greater erosion.

In the second edition of this book, commenting on the supposed separation of the eastern and western seas, I remarked that this separation was a doubtful question, and that there must have been some direct communication between the sea of the Coralline Crag and a more southern sea, because of the large proportion of Mediterranean species in its molluscan fauna, namely 205 out of 250 living species, 51 of them being now restricted to southern seas.

Mr. C. Reid had then published his opinion that all the older Pliocene deposits of Britain were laid down in about the same depth of water, and that the period was generally one of submergence, "though the indications of irregular movement prevent us feeling confident, in the absence of fossiliferous deposits, as to the extent of the submerged area."[1] He also observed that the height of the Lenham Beds above the sea (620 feet), added to the probable depth of water in which they were deposited (240 feet), indicates a subsequent upheaval of the Wealden area to an extent of at least 860 feet, and that if Southern England were now depressed to this extent, none of it, except a few hill-tops, would rise above the sea. Moreover, though he did not commit himself to the view that there was direct connection between the eastern and the south-western seas, he did admit (p. 189) that there must

[1] "The Pliocene Deposits of Britain," *Mem. Geol. Survey* (1890), p. 70.

have been "free connection between the German Ocean and more southern seas" by some channel or other.

More recently Mr. F. W. Harmer, writing on the Lenham Beds in 1898, also expressed the definite opinion that after the close of the Miocene epoch "the German Ocean encroached on the land over the west of Belgium and the Pas de Calais towards Kent, opening up communication with seas to the south-west."[1]

Notwithstanding his expression of this view the map illustrating the paper referred to shows no indication of an opening across France or Kent from the Anglo-Belgian sea towards the area of the English Channel; on the contrary, the southern limit of the Diestian sea is represented as a continuous line from Belgium to Kent, the only break being to the south of Tournai in Belgium, which the Belgian geologists interpret as evidence of the estuary of a river coming from the south and opening northwards into the Diestian sea.

The channel-opening on Mr. Harmer's map leads westward beyond its limits across Essex and up the Thames valley. He has been kind enough to explain that the idea in his mind was a channel across "some part of the S.E. of England," and if the curve on his map were prolonged it would be carried through Surrey and Western Sussex to the Isle of Wight. It seems to me, however, much more reasonable to place the connection across that space where existing Pliocene deposits come nearest to one another, *i.e.* between Calais and the Cotentin, a distance of a little over 200 miles, rather than to imagine it as passing over a longer and more circuitous route, along which no traces of Pliocene deposits have been recognised, and for which there is no confirmatory evidence.

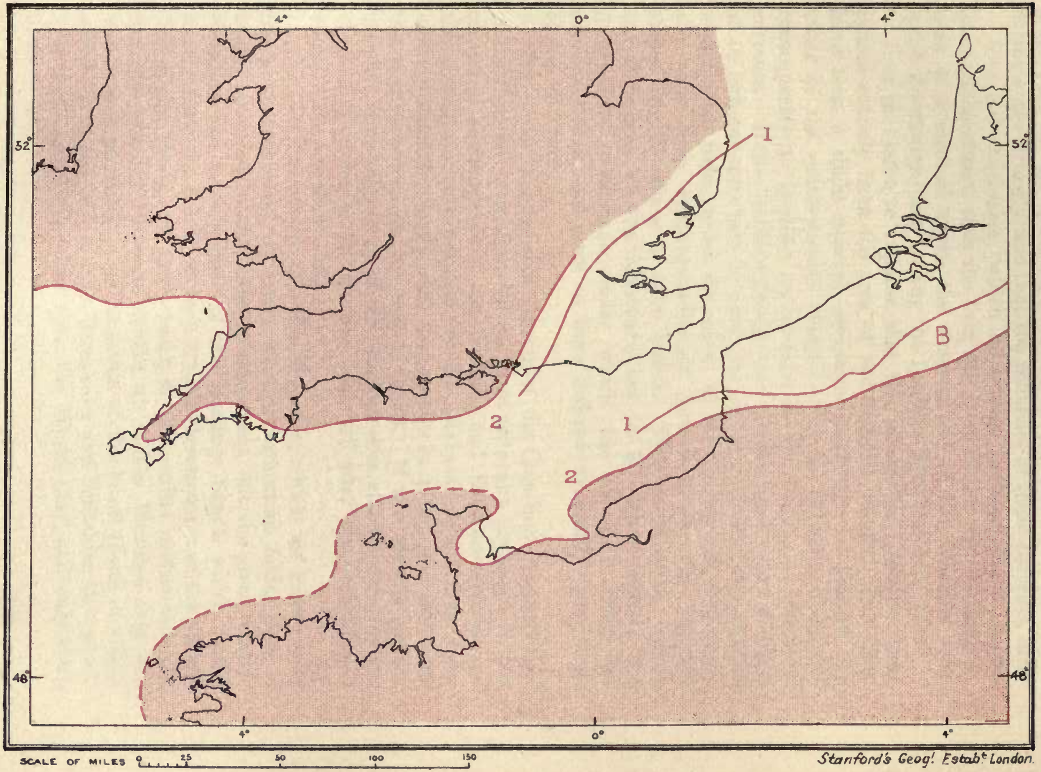
We have next to consider whether any great change in these geographical conditions occurred between the formation of the Lenham Beds (Diestian) and the Coralline Crag (Casterlian). On this point again the views expressed in Mr. Harmer's papers are somewhat conflicting. In 1898 he wrote in his summary of conclusions:—

"2. That the Lenham Beds had probably been upheaved, consolidated, and exposed to denudation before the deposition of the Coralline Crag, and may have been . . . the source from which the boxstones found at the base of the Suffolk Crag have been derived."

"3. That in the interval between the deposition of the Lenham Beds and the Coralline Crag the Crag sea retired, in consequence of the upheaval of the southern part of the area, to the north, as it did also in Belgium."

[1] *Quart. Journ. Geol. Soc.* vol. liv. p. 315.

Fig.71.—GEOGRAPHY OF LOWER PLIOCENE TIME.



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His 16th conclusion, however, is "that during the deposition of the Coralline Crag the German Ocean was less open to the north than it is at present, if indeed it was not entirely closed, but that it was connected with the Atlantic by a strait or channel over some part of the southern counties of England, through which currents ran strongly, and that the influence of these currents, etc."

The last conclusion, which he repeats in later papers, seems almost inconsistent with the first, for it would involve the keeping open of a channel across the western end of the Wealden area, while the eastern part bearing the Lenham Beds had been raised!

I see no reason to suppose that the sea of the Coralline Crag retired entirely from the area of the Diestian Sands; there may have been a slight upward movement, sufficient to shallow the water of the south-western channel over the Wealden area, and consequently to produce an increase in the velocity of the local currents. If the Lenham Sands were accumulated under a depth of 40 fathoms (240 feet) of water, an elevation of half this amount would bring them under the action of strong currents, and would also raise beds contemporaneously formed nearer the Diestian shores into the plane of tidal action. This would quite explain the derivation of the boxstones, but in all other respects the geographical conditions under which the Coralline Crag was accumulated do not seem to have differed materially from those of Diestian time.

The connection between the sea of the Coralline Crag and that of the Channel area seems to me most naturally explained by the continued submergence of the Wealden and Boulonnais areas, and the strong currents assumed by Mr. Harmer would then come directly from the south-west, as he states in print, and not from the west, as shown on his map of 1898. If this view is correct, then the final bulging up of the Wealden area and the interruption of the S.W. currents did not take place till after the Casterlian or epoch of the Coralline Crag.

The flexures within the Wealden area, which we know to be the prolongations of the more western Armorican folds, were of course produced by the Miocene movement, but the great relative elevation and protuberance of the Hastings Sands, which would have carried the Chalk to such a high elevation above the central part of the Weald, was not a result of this earlier movement. In fact, but for the Pliocene arching up of the Wealden area this would now be merely a prolongation of the broad plains of Chalk which lie to the west of it in Hampshire and Wiltshire, the central axes exposing nothing older than the Weald Clay, and only small areas of that.

In this connection the difference in the position of the main watershed is especially notable; in Wiltshire and Hampshire it corresponds with the most northern axis, while in the Wealden area it corresponds with the central axis. If the latter had been prolonged westward in Pliocene time, the courses of the Hampshire and Wiltshire rivers would not have been as they now are.

I think, therefore, that the Pliocene uplift was restricted to the Wealden area, and to the tracts in France and Belgium where the Diestian Sands are found at high levels. The fact above noted (p. 406) that as the patches of these sands are followed eastward their height above sea-level diminishes, is strong evidence that the vertical uplift died out in that direction: consequently it is a fair inference to suppose that it died out in a similar manner toward the west, and was in fact concordant with the western termination of the Weald. This supposition has the further advantage of accounting for the great extent and protuberance of the Wealden pericline, as compared with the much smaller periclines that occur along the Armorican flexures to the westward.

Mr. Harmer's views with regard to the relative date of this uplift seem to have undergone some change since 1898, for his latest expression of them agrees so closely with those which I have stated above that I am glad to quote them. Writing on the Pliocene deposits for the Jubilee Volume of the Geologists' Association, he remarks:[1] "The decidedly southern character of the fauna of the Coralline Crag period seems to indicate that the Pliocene basin at that time, as during the Lenham stage, was connected with the English Channel and the Atlantic over some part of the south-east of England, and closed to the north; but during the interval separating the Coralline and the Red Crags these conditions were reversed." With the views thus expressed I entirely concur.

On the other side of England we have proof that Cornwall lay at a lower level than it does now, large portions of its southern and central parts being submerged, so that the Atlantic waters spread across it and passed eastward up the central and southern parts of the English Channel. The fauna of the St. Erth Bed exhibits the same prevalence of southern species as that of the Coralline Crag, while the absence of Arctic forms led Messrs. Kendall and Bell to believe that the Arctic Ocean did not then open into the Atlantic,[2] but that the land communication which is believed to have existed between Europe and North America in

[1] "Geology in the Field," *Proc. Geol. Assoc.* (1909), Part I. p. 91.
[2] *Quart. Journ. Geol. Soc.* vol. xlii. p. 201 (1886).

Eocene time (see p. 372) continued to exist through the Miocene and early Pliocene periods, so as to form a barrier of separation between the Arctic and Atlantic Oceans.

If this tract of comparatively shallow water was land, as it is believed to have been in Eocene and Miocene times, and if Greenland was then united to America, as is most probable, no Arctic currents could have entered the Atlantic Ocean, and the climate of its northern shores would be much milder than at present. Under such geographical conditions Greenland and Iceland may have been fitted to support a luxuriant flora, as they undoubtedly did in Eocene times; for Dr. A. R. Wallace observes that "the existence at the present time of an ice-clad Greenland is an anomaly in the northern hemisphere, only to be explained by the fact that cold currents from the polar area flow down both sides of it."[1]

We now come to Middle Pliocene time, that of the Red Crag and of the much thicker Scaldisian and Amstelian deposits of Belgium. This epoch opened, as Mr. Harmer has shown, with a movement *à bascule*, a tilting or compensatory movement, involving a rise in the south (as already described) and a subsidence in the north over the whole area of Eastern England, the North Sea, Belgium, and Holland. Writing in 1900 he says: "The principal difference between the Coralline and the Walton horizons is that the Waltonian Beds contain a number of Mollusca which, during the interval separating the two periods, had invaded the Crag basin, presumably from the north, owing probably to the opening up of communication with northern seas by the tectonic movements referred to in my former papers."[2]

This is exactly the view which I took in 1892, as will be seen from the following passage, which appeared in the second edition of the present work: "This subsidence [*i.e.* of the Red Crag time] carried the sea northwards far beyond its former limits, submerged the land which had hitherto united Scotland to Scandinavia, and so opened up a communication between the North Sea and the Arctic Ocean. Further, in all probability by the breaching of the isthmus between Scotland and the Faroe Islands, and by the conversion of the deep valley or hollow north of these islands into a strait, a temporary connection was effected between the Arctic and the Atlantic Oceans. By these passages many North Atlantic and American species of mollusca gained access to the Anglo-Belgian part of the Pliocene sea, no fewer than eighteen American species occurring in the newer Crags, only

[1] *Island Life*, 2nd Edition, p. 154 (1892).
[2] *Quart. Journ. Geol. Soc.* vol. lvi. p. 707.

seven of which still live on the Scandinavian coast, the remainder being now confined to the North American region."

Confirmation of this view is found on the coast of Aberdeenshire, between the mouths of the river Ythan and the Water of Cruden, where the cliffs show a great thickness of sand and sandy gravel containing broken shells of Crag Mollusca, and overlain by a red boulder-clay. These deposits have been studied by Mr. Jamieson, who thinks "that some patch of crag may have occurred along the coast, or occupied part of the low ground near the estuary of the Ythan, and had been scoured out by the ice coming across it from the southward."[1] It is clear at any rate that beds of Crag existed in Aberdeenshire during the glacial period, and the presence of such species as *Astarte mutabilis*, *Turritella incrassata*, and *Voluta Lamberti* makes it certain that they included a representative of the Red Crag.

The Red Crag of Suffolk seems to have been formed in a bay, or rather a shifting succession of bays on the western side of an open North Sea; while the Scaldisian and Amstelian sands of Belgium were deposited in the deeper part of the same sea, and probably consist of material poured into it by the Rhine. The thickness of these deposits proves that the subsidence went on for a considerable length of time, and it seems to have reached its greatest extent near Amsterdam, where the base of the Amstelian was not reached at a depth of 1100 feet.

Passing now to Upper Pliocene time and the consideration of the conditions under which the Norwich Crag was formed, we find that it occupies a larger area in East Anglia, and that as a consequence of continued subsidence a much greater thickness of deposit was there accumulated (see p. 410).

On this point Mr. Harmer has remarked that "this movement of the Pliocene sea-bottom in Holland was coincident with, if not caused by, the accumulation of the sediment brought into it by rivers; and as the Dutch deposits represent the ancient delta of the Rhine and its affluents, it seems more than probable that the micaceous sands of the Norwich Crag, although not contemporaneous with the Amstelian strata, also may have had a similar origin; the heaping up of sand and of dead shells against the western margin of the Crag sea being favoured by the prevalence at that time of easterly winds."[2]

At the time of the Chillesford Beds the subsidence had either come to an end or had become so much slower that it could not keep pace with the deposition of material. Consequently it

[1] *Quart. Journ. Geol. Soc.* vol. xxxviii. p. 154.
[2] *Ibid.* vol. lvi. p. 735.

appears that all the southern part of the North Sea, from Norfolk to the northern border of Belgium, was silted up and formed a huge delta through which the Rhine and other rivers made their way by numerous and devious channels. The Chillesford Clay, as mentioned on p. 410, was itself formed in the channel of a winding estuary at the termination of one of these channels, and may actually have been a deltaic branch of the Rhine.

Coming now to the final phase of the Pliocene epoch, it is probable that at the time of the Cromer Beds much of the southern part of the North Sea area passed into the condition of a broad plain of dry land studded with large shallow lakes, like the *broads* of modern Norfolk. Such is the opinion which Mr. C. Reid was led to form from a study of the Forest Bed and its associated deposits ; and the following remarks are quoted from his Memoir :[1] "The large number of mammals already known from the Forest Bed seems clearly to point to a connection with the continent" ; but "both the fauna and flora, leaving out the large mammals and other extinct forms, are curiously like that of the 'broad' district of Norfolk at the present day ; and this, like the rest of the evidence, points to a wide alluvial plain with lakes and sluggish streams, bounded on the west by a slightly higher sandy country, covered with fir-forests and distant from any hills."

It is supposed that this plain was traversed by a large river coming from the south-east, as stated on p. 410, and that this river was no other than a continuation of the Rhine ; a view first suggested by Mr. Gunn in 1867, but adopted and strengthened by subsequent writers. Thus Professor Prestwich, writing in 1871, remarks that on the tableland above the Meuse in Belgium there is a gravel of very similar character, and though, according to Mr. C. Reid, this contains veined quartzites of a character unknown in the Forest Bed gravels, yet the general similarity of the gravels suggests that they belong to one and the same system of drainage. Mr. Reid himself suggests that the fragments of Carboniferous slate and chert may have been derived from rocks that "came to the surface as part of the old ridge which Mr. Godwin-Austen has described" ; the Ardennes are part of this ridge, the Meuse was a tributary of the Rhine, and it is to the Rhine that Mr. Reid refers the transport of the pebbles in question.

In the preceding pages we have been mainly concerned with the geography of Eastern England and the North Sea, but the western part of the British region must not be left out of account. Notwithstanding the absence of Pliocene deposits in the western areas, they must be considered in the light of such evidence as

[1] *Geology of the Neighbourhood of Cromer*, pp. 60, 61.

exists in order that a proper conception of the geography of the whole region may be formed.

We have seen that, after the rise of the Wealden area and the formation of the North Sea, there was a continual tilting to the north, or more probably to the north-east, considering the great thickness of the newer Pliocene below Amsterdam. Consequently the south and S.W. of England, with the whole Channel area, may have been raised considerably above the level at which they stood in Lower Pliocene time. The probability of this is increased by the fact that there are no marine Upper Pliocene deposits in Normandy nor at any other place on the borders of the English Channel, the only Upper Pliocene in France being a river gravel near Chartres.

The absence of any marine Upper Pliocene beds along the west coast of England and the opposite coast of Ireland is in itself of small significance, for if such beds ever existed at low levels they might have been destroyed by subsequent erosion or submerged by subsequent subsidence; but the further fact that no characteristic Pliocene shells are mingled with those found on the Glacial Drifts of Ireland, Wales, and Lancashire is one of great importance; for if Pliocene deposits had existed in the basin of the Irish Sea they would have been swept out by the ice along with those of Pleistocene age.

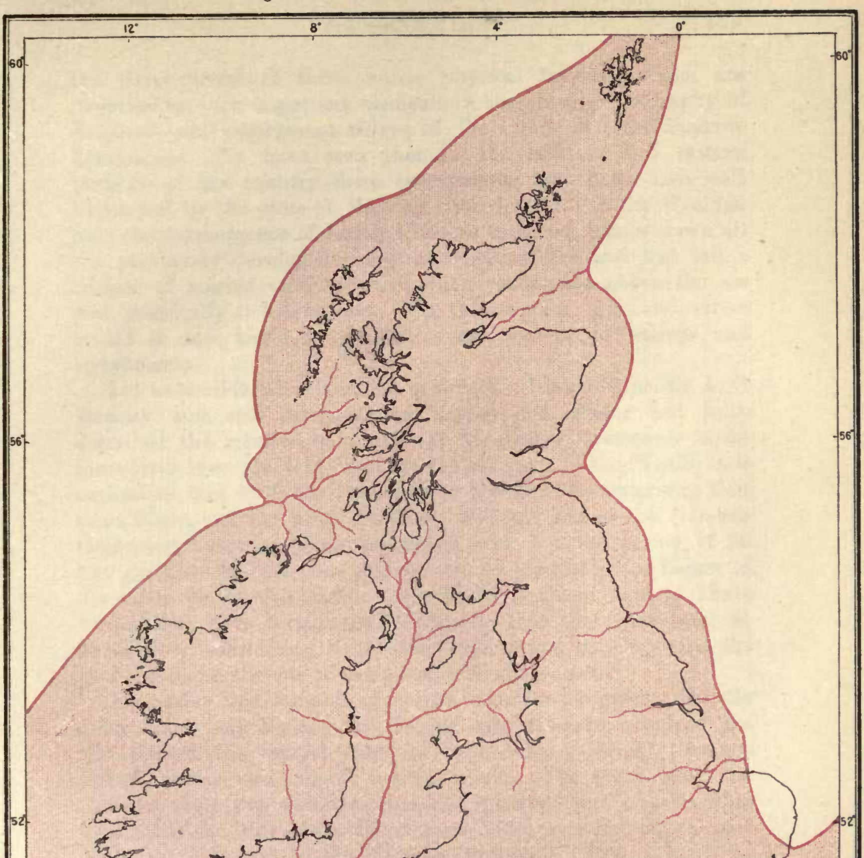
Consequently I agree with Professor Boyd Dawkins's view that the Irish Sea and St. George's Channel remained in the condition of a land-surface throughout Pliocene time, and that the close of the period found Ireland and England still broadly united to one another and also to France; the western coast-line of the British region coinciding approximately with the present 100-fathom contour.

Professor Dawkins first embodied this view in a map in his *Early Man in Britain* (1880), and more recently prepared a corrected map of the British Isles in Upper Pliocene time.[1] With this later restoration of Pliocene geography I concur in all essential particulars, differing only with regard to the course of the river which must have traversed the Irish Sea (see Fig. 72). Professor Dawkins marks it as running northwards through the North Channel instead of southward through St. George's Channel. The northerly course is possible, because the present soundings are no indication of the relative levels of the Pliocene surface, and the sea north of Ireland is doubtless choked with Glacial deposits, but so also is St. George's Channel, and on general grounds I think the original outlet of the rivers entering the Irish Sea area was southward.

Lastly, let us see what progress is likely to have been made in

[1] *Quart. Journ. Geol. Soc.* vol. lix. p. 127 (1903).

Fig. 72.—GEOGRAPHY OF UPPER PLIOCENE TIME.



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the development of those minor physical features, which are nevertheless such important elements in the physical geography of England—the escarpment ridges of the Chalk and the Jurassic Limestones. We have seen that in the midland and eastern portions of the country these escarpments must have been well developed by the close of Miocene time, but that in the Wealden area the submergence of Lower Pliocene time had planed down all the previously developed ridges and inequalities, and had left a surface of marine erosion, which when re-elevated above the sea was practically a *tabula rasa*. On this surface rain and rivers would at once begin to establish a new system of valleys and escarpments.

Let us consider this Wealden area first. Inasmuch as Sir A. C. Ramsay and, still later, Messrs. Topley and Foster had fully described the manner in which all the Upper Cretaceous rocks must have been removed from the central parts of the Weald, it is curious to find Professor Prestwich so late as 1890 supposing that some Chalk and the whole thickness of Gault and of the "Lower Greensand" remained over the central area "at the period of its last emergence." On this assumption he calculated the height of the dome before denudation to be 2600 feet, and says: "There would thus have been, even supposing that there has been no subsequent subsidence, a low mountain range running into the Boulonnais, on the site of the present Wealden area."

I consider this estimate of height to be far too great. On the other hand, both Ramsay and Topley seem to have imagined the rise toward the central ridge to have been so slight that the general surface was almost a level plane. The truth must lie between these two extremes, and the question really is, To what height was the floor of the Diestian sea lifted over the central part of the Wealden area by the Pliocene elevation? This can only be ascertained by making some assumption as to the actual slope of the plane on which the Diestian Sands now rest. On p. 391 I have given reasons for assuming that between Sheppey and Lenham this plane rises 300 feet in 9 miles, and that 16 miles south of Lenham it would have reached a height of 1130 feet. There is very little further assumption in supposing that the slope of the plane was about the same in the western part of Kent, north of Crowborough and Tunbridge.

Now the escarpment-ridge of the Chalk near Wrotham is 774 feet above sea-level, and if the position of the Diestian plane was analogous to that which it occupies near Lenham, it would have passed over the summit a little above this level, say at 784 feet. The distance from the ridge to Crowborough Beacon is 17 miles, and if the upward slope continued at the rate above mentioned, the plane would rise another 566 feet, which, added to the height near Wrotham, makes 1350 feet.

This, therefore, may be taken as the approximate relative height of the central ridge of the Wealden area when the Pliocene uplift was completed; and as the base of the Red Crag in Suffolk is not far from present sea-level, this height may be taken as approximately that of the Pliocene watershed above the level of the Red Crag sea—which is what we want to know. Thus subsequent movements in the east of England can be ignored.

The thickness of Hastings Beds above Crowborough Beacon may have been more than 600 feet, according to details given in Topley's Memoir, so that probably a little of the Tunbridge Wells Sand would have been exposed at a level of 1350 feet, but it would only form a narrow outcrop along the ridge and would be surrounded by broad plains of the Weald Clay, sloping very gently to the outcrops of the Vectian Beds.

Such in my opinion was the surface on which the present drainage system of the Wealden area was established, and of course the continuation of this surface passed over the basset exposures of the Gault, the Chalk, and the Eocene Beds in their regular succession. All the principal streams would at first run off the central ridge, and would form transverse valleys across the outcrops of these beds. Doubtless there were originally many of them, but on the northern side only four now survive to traverse the North Downs; these are the Wey, the Mole, the Medway, and the Stour. On the south side there are also four such rivers—the Arun, the Adur, the Ouse, and the Cuckmere; but, as Topley pointed out, there was almost certainly another to the eastward, for the prolongation of the Ashburn brook must have reached that part of the South Downs which has been destroyed by the sea since Pliocene time.

There are several high-level passes through the Chalk escarpments both of the North and of the South Downs, and it is generally supposed, with good reason, that these are the relics of the deserted valleys of rivers which once ran over the Chalk at such levels, but whose sources have been captured by longitudinal streams forming valleys along the strike of the beds, more or less at right angles to the old transverse valleys. The development of these longitudinal streams and of the parallel escarpments of the Vectian Sands and the Chalk is a process so well understood and explained in all text-books that there is no need for me to dwell upon it here.

Further, I may say that the only new point in the above explanation of the physical features of the Wealden area is the estimate of the probable height of the central ridge and of the stratigraphical level to which the area had been reduced by Miocene denudation and the Diestian marine erosion. All the rest is simply a brief re-statement of the views expounded in the first place by Sir A. Ramsay, and more fully by Messrs. Topley and Foster,[1] to whose writings I refer the reader.

Every geologist knows that the Weald is a typical instance of the development of a system of river-drainage out of a surface of such low relief as to be almost a plain or plateau. Such a surface is now generally called a peneplain, or, as the word should be written more correctly, a peneplane. The origin of peneplanes is, however, a disputed question; Professor W. M. Davis has propounded a theory that most if not all peneplanes have been formed by subaerial detrition, and his able exposition of the theory has invested it with a halo of probability. I desire, however, to express my dissent from his views. The production of a peneplane by such detrition may be a theoretical possibility, but I think it has very seldom if ever been accomplished.

The effect of subaerial detrition on a surface composed of several different kinds of rock, even if all are soft, such as clay, sand, and marl, is to develop inequalities. It is universally admitted that these inequalities arise from the inherent differences of the rocks and from their varying powers of resistance to detritive agencies. This differentiation is only increased by continued exposure until every stream has found its base-level of erosion. It is true that ridges and watersheds will still continue to be lowered by the action of rain, wind, and frost, and by the creep of soil down their slopes; but this process will become slower and slower as the angle of incline decreases, and the final result would be a peneplane consisting of the same inequalities reduced to a minimum of low relief, without any material alteration of the system of drainage which had been so long established.

Moreover, in most cases before this final result had been attained some earth-movement would have intervened to alter the physical conditions. Either a general elevation would take place, creating a new cycle of erosion along the old lines, or subsidence would carry the sea over the area and produce a plane of marine erosion.

In the case of the Weald the evidence for the marine origin of the peneplane seems particularly strong. This evidence is found not only in the plane of the Diestian Sands, but in the absence of

[1] *Quart. Journ. Geol. Soc.* vol. xxi. p. 443 (1865); and "Geology of the Weald," *Mem. Geol. Survey*, p. 270 (1895).

flints over the whole central portion of the Wealden area. Moreover, the Vectian Sands contain cherts which are nearly as indestructible as flints. During the subaerial detrition of the area in late Miocene time great quantities of cherts and flints must have accumulated on the surface, and large tracts of them must have been left on the watersheds. Remnants of these plateau gravels would be left now if they had not been removed by the action of the sea.

Indeed it is somewhat astonishing that they should have been so completely removed, for, as Topley remarked in his Memoir (p. 287): "We might reasonably expect to find here and there, near the border [of the Hastings Beds], a few flints remaining on the surface. The occurrence then of an occasional flint in the gravel should not surprise us; rather should we be surprised at their being so rare that weeks of careful searching have failed to find them in all but two places."

Topley has also shown that wherever flints are found abundantly on the surface of the Weald Clay, they have clearly been carried thither by streams flowing from the inner side of the Chalk escarpment, while in the gravels of streams which flow off the Weald Clay or Hastings Beds, only pebbles derived from those formations are found. Again, it is only for a certain distance inside the escarpments of the chert-bearing sands that fragments of chert are found. These occur both in river gravel and as patches of angular chert gravel capping some of the hills; and, writing of those on the northern side of the Wealden area, Topley remarks that "they are evidently either the actual remains of the Lower Greensand escarpment, or a wash from that escarpment, when it reached farther south than now" (*op. cit.* p. 290).

Finally, let us endeavour to realise some of the changes which must have occurred in other parts of England during the later part of Pliocene time. The uplift of the Wealden-Artois watershed in the south, and the subsidence of the whole area of the North Sea and possibly of North Britain, must have considerably modified surface conditions in the east of England.

In the first place, the curvature of the London basin must have been accentuated. It doubtless came into existence as a shallower basin in Miocene time, after the uplift of Southern England along Armorican lines; but the further uplift of the whole Wealden area after the Diestian submergence must have raised the southern limb of the syncline and have thereby increased the relative depth of the London basin. At the same time, whatever may have been the course of the Miocene precursor of the Thames the planation of the Diestian sea must have destroyed or submerged the lower part of its valley, and the post-Diestian uplift must have determined the line of the present wide valley within which the Thames winds from Reading to Greenwich.

With regard to changes farther north it has been supposed that a greater easterly tilt was imparted to the east of England by the subsidence of the North Sea region. This subsidence certainly brought the sea of the Red Crag as far west as Sudbury, and that of the Norwich Crag as far west as Norwich and perhaps a little farther; but it does not necessarily follow that the easterly dip of the Mesozoic rocks was increased. Such increase depends on whether the movement was a general one, affecting all the northern part of the British region, or a partial one creating the depression of the North Sea. There are several facts which favour the former and not the latter view, *i.e.* a northerly and not merely an easterly subsidence.

The arrangement of Pliocene deposits both in England and in the Netherlands indicates a tilt to the north, allowing northern waters to come in, but to cover *less and less* of the southern part of the area; for the Coralline Crag had been raised before the Red Crag was deposited over part of the area it had occupied, and the Red Crag was apparently being lifted above sea-level during the accumulation of the Norwich Crag. Thus the area of land increased in the southern part of the North Sea and its borders, while it decreased toward the north.

Again, there is a very notable decrease in the height of the escarpment of the Upper Chalk when it is followed from Hertfordshire through Cambridge, Suffolk, and Norfolk; and this may be largely due to the northerly tilt of the whole area. It is probable too that this tilt, combined with a previous breaching of the escarpment by some river from the west, subsequently enabled the sea to break through and form the bay of the Wash.

It has been thought that more than one river from the Eastern Midlands may have entered the sea of the Norwich Crag. Prestwich long ago recorded the occurrence of Lias Ammonites and Carboniferous Corals in the crag at Norwich, but the existence of such fossils is no proof that they were carried into Norfolk by contemporaneous rivers; for they may have been derived from older river gravels of Miocene date, when rivers from the Midland area probably did cross the surface of the Chalk in several places. Of these rivers only one (the Humber) now survives, but it is very likely that another lasted into Pleistocene time and passed through the gap of the Wash. This river was probably a union of the rivers Trent and Welland, if the former at that time passed through the Lincoln gap, as it certainly did at a later epoch.

During the lapse of Pliocene time the valley system, which had been initiated in Eocene time, and had been more deeply incised and developed during the Oligocene and Miocene periods, was practically completed ; so that by the close of Pliocene time the country must have presented a very similar appearance to that which it now possesses. The great plains of the Lias and Upper Jurassic clays were as broad then as they are now, for the Jurassic and Cretaceous escarpments had by that time retreated to the positions which they now occupy. This we know by the manner in which the Glacial deposits were banked against the fronts of them, as, for instance, in Rutland and Lincoln against the Jurassic escarpment, in the counties of Hertford, Cambridge, and Lincoln against the Chalk escarpment.

CHAPTER XVI

THE PLEISTOCENE PERIOD

THIS period may be taken to include all the time which elapsed between the close of the Pliocene and the earliest epoch of which we have any historic knowledge; it may in fact be taken to cover the whole of post-Pliocene and prehistoric time. But though it is thus the latest of the geological periods, and in spite of the greater perfection of the records left for our examination, its interpretation is in some respects more difficult than that of earlier Tertiary periods.

No general classification of Pleistocene deposits has yet been framed which can be applied to more than a limited portion of the British Isles, such as East Anglia or Wales. Even a general division into Glacial and post-Glacial is equally local, for the so-called Glacial epoch was only an episode in Pleistocene time, and its special products are limited to the northern parts of Europe, not extending even into the southern part of England. Hence glacial conditions persisted in Scotland long after they had disappeared from Central and Eastern England.

The Glacial deposits are, however, of sufficient thickness and extent to play an important part in the final modelling of the surface features of our islands. The principal product of the Glacial epoch or "Great Ice Age" is the material known as boulder-clay, of which there are several varieties; some of those clays are stiff and almost hard, owing to the great pressure of the ice under which it was accumulated, others are marly or chalky, and others again are loose and sandy, with indications of stratification, often including layers of gravel and sand which sometimes contain marine shells.

As this book is only concerned with the building of the British Islands and the geographical phases through which they have passed, we need only consider the Pleistocene deposits from two general points of view: (1) as so much new material added to the structure of certain areas; (2) as new features which led to considerable alterations in the surface-drainage and river systems of the country. After considering the distribution of these surface-deposits and their geographical consequences, we may conclude with a review of the changes of level which took place in Pleistocene time, and finally effected the severance of Britain from the European continent.

A. *Distribution of the Glacial Deposits*

Viewed as so much constructional material the Pleistocene deposits are chiefly those of Glacial origin, and it will suffice to give a general account of these without entering into any discussion of the special conditions under which they were accumulated. Under the head of Glacial deposits must be included not only boulder-clays and the unstratified gravels often associated with them, but also the stratified sands and loams and shelly clays which were clearly deposited in water, whether the water was that of a glacial lake or of some inlet of the sea blocked by an outer barrier of ice.

The Glacial deposits are thickest on the lowlands which lie between the hilly and mountainous parts of the country, and over the marginal or coastal tracts; while they thin away toward the higher mountain districts, from which much of their component materials have been transported. In the east of England, however, some of the material seems to have been carried inland from the North Sea, and it includes stones which have actually travelled across that sea from Norway and Sweden. The following is a brief account of the distribution of these Glacial deposits in England, Scotland, and Ireland respectively.

1. England and Wales.—The Glacial Drifts of England and Wales may be considered as the products of four principal ice-fields coming from different directions: viz. (1) the Welsh ice, (2) the Irish Sea ice, (3) the Northern ice, (4) the North Sea ice; and besides these there seems to have been a small independent snow-field on the southern part of the Pennine Hills. The map (Fig. 73) is an attempt to indicate the areas over which these ice-fields extended at the epoch of maximum glaciation, but the limits of these areas have not yet been accurately determined.

The Welsh ice originated in glaciers descending from the mountains of Wales and radiating outwards in all directions, but mainly to the north-west, west, south, and north-east. Probably there were three centres of dispersal—the northern comprising the Snowdonian and Merionethshire mountains, the central from the Plynlimmon district, and the southern from the Brecknock Beacons.

For some reason Hereford and the southern part of Shropshire are almost free from Glacial Drift.

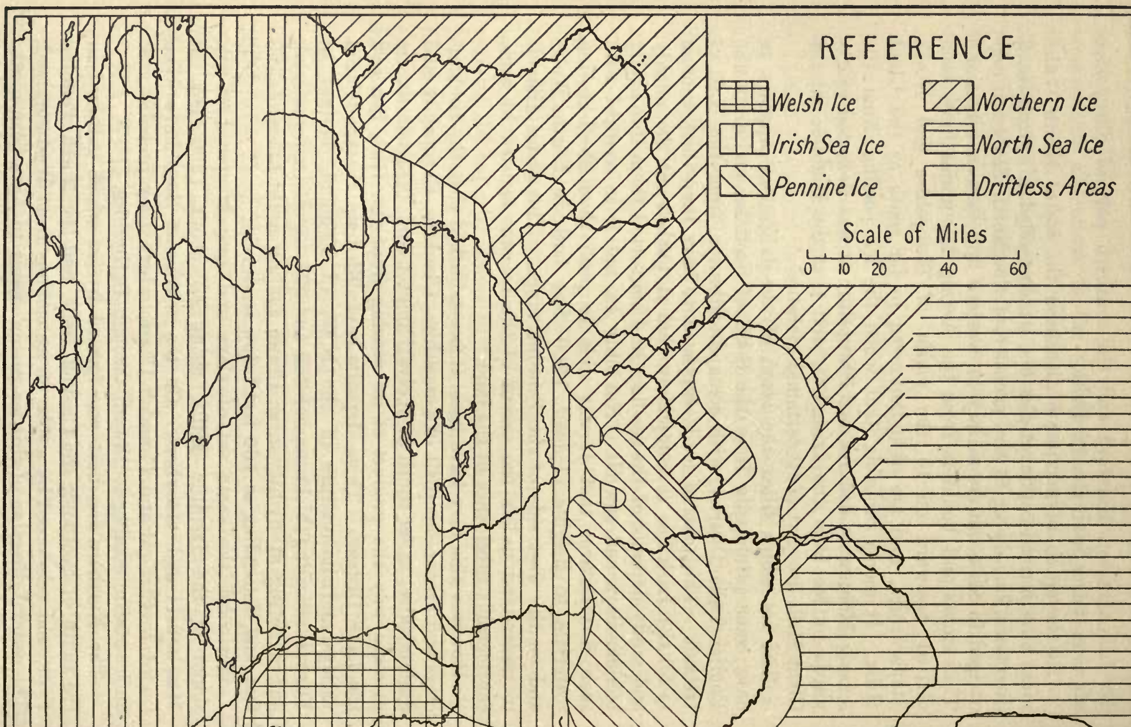
At the epoch of maximum glaciation the ice of North Wales must have formed confluent glaciers, which tended to spread in all directions, but owing to the pressure of the North Sea ice it was obliged to seek outlets mainly in western and eastern directions. Thus stones and boulders from the Arenig Mountains have been carried eastward on to the plains of Shropshire and North Staffordshire, and are abundant even so far south as the Clent Hills. It seems probable that when the ice coming from the Arenig Mountains had reached Shropshire it was deflected southwards by ice from the Irish Sea, and that the boulders on the Clent Hills are part of its terminal moraine.

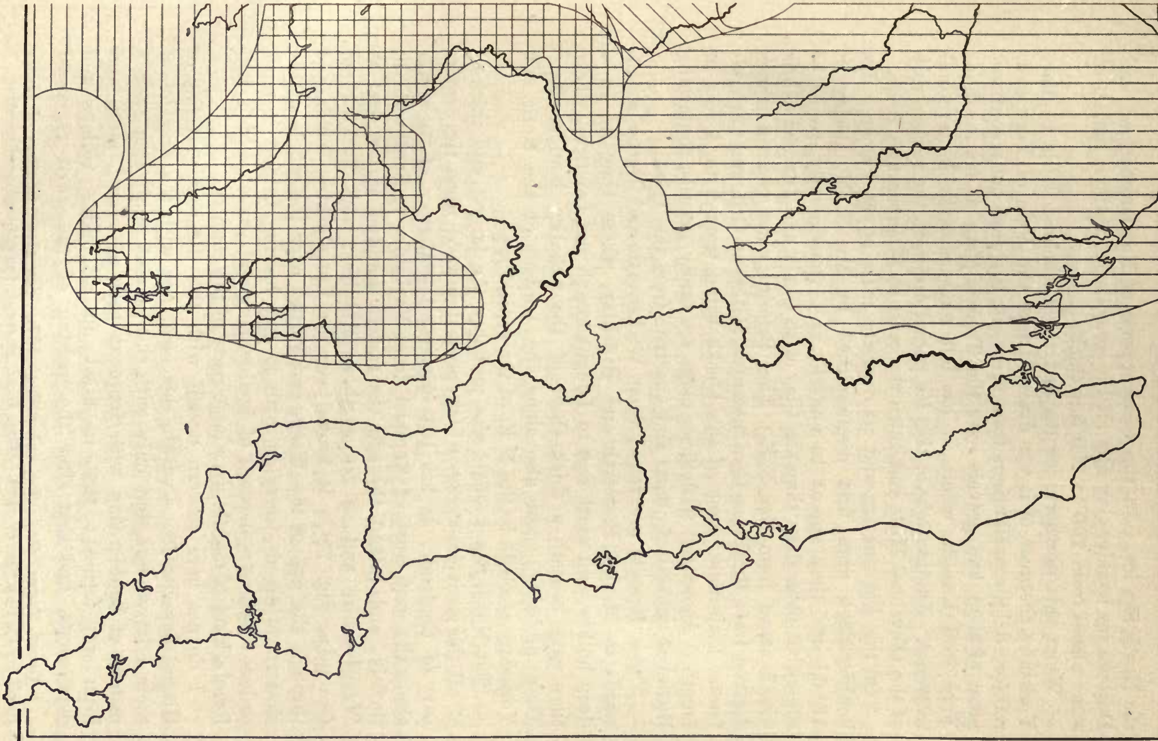
The ice which filled the basin of the Irish Sea appears to have come principally from the S.W. of Scotland and from the English Lake District, with some contribution from the N.E. of Ireland. This mass of ice is supposed to have been thick enough to fill the Irish Sea so completely that it pushed out the muddy and sandy deposits of the sea-floor and converted them into shelly boulder-clays and gravels. Not only so, but it is credited with such a *vis-a-tergo* that it was able to push these shell-bearing materials to heights of over 1200 feet both in North Wales and on the west side of the Pennine range. This seems difficult to understand unless the ascent of the ice was assisted by some considerable subsidence of the land.

However this may have been, it is established that the boulder-clays and arenaceous drift of Lancashire, Cheshire, Shropshire and Staffordshire, as far south as Wolverhampton and Bridgenorth, are in some way the product of ice coming from the Irish Sea and the Lake District. These deposits have filled up the pre-Glacial valleys and inequalities of the N.W. of England, borings in Furness revealing thicknesses of 369 and 537 feet of Drift material, and a boring at Sydney near Crewe finding a thickness of 320 feet, and descending to 160 feet below sea-level.

Eastward the same set of clays and gravels spread to the slopes of the Pennine Hills, rising to about 1200 feet at Macclesfield and elsewhere. On the south-east they have been traced to Stafford and Cannock Chase, where they probably met an ice-stream coming southward through Derbyshire.

The Northern ice-sheet was formed by ice which gathered in the south of Scotland, the Cheviot Hills, and the North Pennine Fells, and reinforced by a lobe of ice coming from Westmoreland. The general direction of this ice-stream seems to have been southward, the reason being that its outlet to the east was blocked by


REFERENCE
Welsh Ice
Irish Sea Ice
Pennine Ice
Northern Ice
North Sea Ice
Driftless Areas
Scale of Miles
0 10 20 40 60



Stanford's Geog^l. Estab^t. London.

Fig. 73.—MAP SHOWING THE PARTS OF ENGLAND AND WALES COVERED BY ICE-FIELDS DURING THE GLACIAL EPOCH.

the North Sea ice. In the eastern parts of Northumberland and Durham its boulder-clay fills all the pre-Glacial valleys, and is in some places from 200 to 300 feet thick.

When this northern ice reached the Cleveland Hills in East Yorkshire the mass of it was diverted into the Vale of York and, reinforced by contributions from the west, it spread out a confused mass of clays and gravels over the Triassic plain as far south as York and Escrick, where it has left some remarkable terminal moraines. Another lobe of this ice passed down on the eastern side of the Cleveland Hills and down the coast to Flamborough Head.

Of the Pennine ice and its deposits little is yet known. Its boulder-clays were first distinguished by Mr. R. M. Deeley in 1886,[1] and they appear to underlie and, consequently, to be of somewhat older date than the Clay with Chalk and Jurassic débris which came from the N.E. The Pennine clays contain stones derived from the Trias, Coal-measures, Millstone Grit, and Carboniferous Limestone, some of the blocks being from 2 to 4 feet in length. Associated with these clays are sandy gravels, containing little but pebbles of quartz and quartzite from the Trias.

These deposits are found from Wirksworth and Derby southwards to Market Bosworth and Hinckley, where they lie in a deep hollow, and south-east to Loughborough and Leicester, where they pass beneath a thick sheet of the "chalky boulder-clay." They probably occur also along the borders of the Notts and Yorkshire coalfield to the N.E. of the typical area.

The North Sea ice-field was probably the largest and thickest of all the great ice-masses which pressed inward upon the central part of England. It has left impressive testimony of its power along the east coast of England from Yorkshire to Southwold in Suffolk, and inland through the eastern counties as far west as Warwickshire and as far south as Middlesex and Buckingham (see map, Fig. 73). It broke over the Lincolnshire Wolds and through the gap of the Wash, and spread over the whole of the Eastern Midlands, carrying with it and leaving behind it more or less continuous deposits of boulder-clay and gravel, which still form a kind of mantle over large parts of the country.

I do not here concern myself with the different varieties of Glacial deposits found within this area, nor with the question of their relative ages, but only with the general result that such a mantle of boulder-clay with frequent beds of gravel, sand, and loam was formed; that it filled up all older valleys and depressions, and that after the melting of the ice it remained

[1] *Quart. Journ. Geol. Soc.* vol. xlii. p. 437. See also "Geology of Leicester" by C. Fox Strangways (*Mem. Geol. Survey*), for general confirmation.

as a partially new surface of ground, on which all brooks and rivers had to make fresh channels for themselves, either along the old valleys or in new directions.

A few words may also be said about the extension of this mantle of boulder-clay beneath the great plain of the Fenland. There can be little doubt that the thickness of the chalky boulder-clay along the wide plain formed by the Oxford and Kimeridge Clays was very great. This clay passes below the Fenland deposits both on their northern and southern borders, and if an old boring at Boston has been correctly interpreted, it has there a thickness of about 140 feet, and its base lies about 175 feet below sea-level; while at Fossdyke, to the south, a more recent boring proved its base to be 156 feet below sea-level. From these facts it is clear that the great gap of the Wash had been formed, and that a deep valley had been excavated in the Jurassic clays during Pliocene or Miocene time, the bottom of this valley being more than 150 feet below the existing sea-level.

There is, however, a certain space within the large area overspread by the deposits of the northern and north-eastern ice-fields which is almost "driftless"; in this space so little Glacial Drift now remains that we cannot suppose any but scanty and sporadic deposits can have been left upon it. This area is naturally divisible into two portions—one consisting mainly of high ground in the N.E. of Yorkshire, and the other of low ground extending from near York southward to Newark and Annesley in Nottingham.

The more northern tract is that of the Cleveland Hills and the northern part of the Yorkshire Wolds, with the broad Vale of Pickering which lies between them. The Cleveland Hills are doubtless the cause of this nearly driftless area, because they diverted the northern ice-flow to the east and west of it. The eastern end of the Vale of Pickering is blocked by a mass of boulder-clay which forms the cliffs near Filey, descending considerably below the level of the sea and rising N.W. of Filey to 200 feet above it. But the width of this barrier is not now more than an average of 2 miles, although it was doubtless originally very much wider, for much has been destroyed by the inroads of the sea.

The ice appears to have been prevented from entering the broad Vale of Pickering by the immense pressure of the northern ice-sheet, which kept off the North Sea ice and was itself forced to flow southward across the eastern opening of the valley. This blocking of the Vale of Pickering had important consequences, which will be described in the sequel.

The other part of the nearly driftless area includes the southern part of the Vale of York and the wide plain of the Trent almost as far south as Nottingham. This tract appears to have been the meeting-place of three ice-sheets, those of the Pennine snow-field, the northern and the North Sea ice-fields. The termination of the northern ice-lobe in moraines near York, and the scantiness of the materials left by the Pennine ice, have already been mentioned; but a very chalky boulder-clay, due presumably to abrasion of the Chalk Wolds by ice from the N.E., spreads on to the eastern border of the plain between Gainsborough and Lincoln, and having got so far it seems curious that it was not carried farther west and S.W. across the valley of the Trent.

I am not aware that any one has yet suggested a reason for the existence of this driftless area, but I am inclined to think it may have been due to the presence of Pennine ice. Owing to the pressure of other ice-fields on the west and north, the Pennine ice could not flow in those directions, and consequently could only escape to the south and west. It may therefore have occupied the Triassic plains of York and Notts in some force, though, owing to its comparatively small snow-field and short journey, it did not carry much clay-making material. It may have carried sand from the Millstone Grits and Coal-measure sandstones, but loose deposits of sand would soon be broken up and removed by water-action on the melting of the ice.

At a late stage in the Glacial Epoch it is possible that a large lake was formed over this driftless area by the blocking of the Humber valley between Hull and Ferriby with Glacial deposits, and by the consequent ponding back of the drainage. But this theory, first suggested by Carvill Lewis,[1] will not account for the absence of boulder-clay in the area, for the lake-waters could not remove it.

2. Scotland.—In North Britain there were three principal centres of ice-dispersion—the North Highlands, the Central Highlands, and the Southern Uplands. The first two gave rise to more or less confluent ice-fields with a combined radial outflow in all directions, as shown in the small map (Fig. 74). The last was a smaller double centre, the Galloway Hills supporting one ice-field with a radiating outflow, which only found free exit in southerly and westerly directions; while another snow-field accumulated on the more eastern hills of Hartfell and Ettrick Moor.

Glacial deposits are thickest and most continuous in the Lowland area between the Highlands and the Southern Hills, but they are found all over the outer parts of the country and in the valleys up to 1800 feet above the sea.

[1] *Glacial Geology of Great Britain* (1894), p. 386.

On the Lowland plain the materials have been derived partly from the Central Highlands, partly from the local Old Red Sandstone and Carboniferous rocks, with some contributions from the Southern Uplands along its southern border. The thickness of the stony clays and gravels varies greatly, because

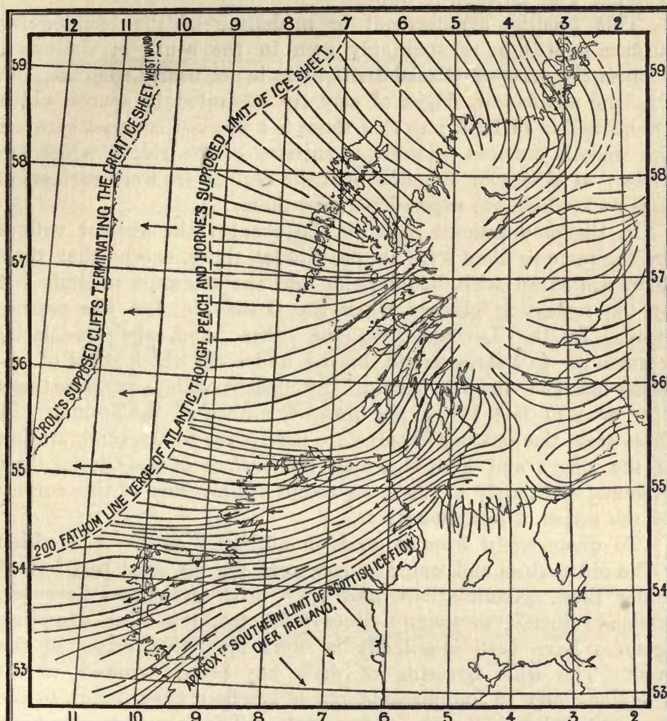


Fig. 74.—MAP SHOWING THE GLACIATION OF SCOTLAND AND THE NORTH OF IRELAND (J. R. Kilroe). (Reproduced by permission of the Author and the Council of the Geological Society.)

both their upper and lower surface is exceedingly irregular, the latter conforming to the inequalities of the pre-Glacial surface and filling up all but its greater depressions, while the upper surface forms an equally irregular series of ridges and mounds.

Sir A. Geikie observes that "the most marked surface feature presented by the boulder-clay of the Lowlands is its tendency to assume the form of long ridges ranged parallel with the general trend of the striæ on the rocks below. . . . In the Lothians, for instance, they run nearly east and west; hence roads which follow that direction may continue for long distances without any marked variation of level, whereas those which run north and south are a succession of rapid ups and downs" (*Scenery of Scotland*, 2nd Edition, p. 363).

This peculiar arrangement or modelling of the boulder-clay surface is still more strikingly seen in the south of Galloway, because the mass of Glacial Drift there is not nearly so great, and the long mounds or ridges of clay are separated by spaces which are quite free of Drift; so that there is a marked contrast between the smooth outlines and grassy surfaces of the ridges, which are known as *drums* or *drumlins*, and the regular ice-worn surfaces of bare rock which are exposed between them.

In the mountainous parts of the country the ancient valleys are the same as they were in pre-Glacial times, except that their floors are paved with boulder-clay and the morainic mounds left by the retreating glaciers when the Great Ice Age was passing away. In the Lowlands, on the other hand, the pre-Glacial features are to a large extent buried under the thick cover of ice-borne material, and the floors of the ancient valleys are sometimes 150 or 200 feet below the present surface of the ground. In these areas the existing features are partly due to the configuration of the ridges and hollows which the surface of the Glacial Drift presents, and partly to the more recent sculpturings of this surface by the action of rain and rivers.

To quote again from so good an authority as Sir A. Geikie: "The old ravines and water-courses were for the most part buried under these accumulations, and only here and there have the streams returned to them. Since then, too, the other denuding agencies have been ceaselessly at work upon the surface of the land. The wide covering of drift has been furrowed in all directions, and in innumerable places has been cut through to the bare rock below by brooks and runnels. The larger streams have dug ravines in it, nay, in numberless cases they have gone farther, and after trenching the drift have even hollowed out deep gorges in the rock itself. Most of the present ravines of the [Lowland] country have probably been excavated since the ice retired."

3. Ireland.—The glaciation of the north of Ireland is interesting from the fact that it was not the same throughout the whole duration of the Glacial epoch. By plotting the recorded directions of glacial striæ on a general map Mr. J. R. Kilroe found that they resolved themselves into two distinct sets.[1] One set seems to

[1] *Quart. Journ. Geol. Soc.* vol. xliv. p. 827.

indicate that the north of Ireland was dominated by the ice descending from Scotland to such an extent that the ice of the Irish Highlands was forced out of its natural lines of flow, and the whole area, from Antrim to Donegal, Mayo, and Galway was glaciated from N.E. to S.W. (see Fig. 74). We may safely assume that these conditions prevailed at the time of maximum glaciation, when the Scottish ice-fields reached their greatest development.

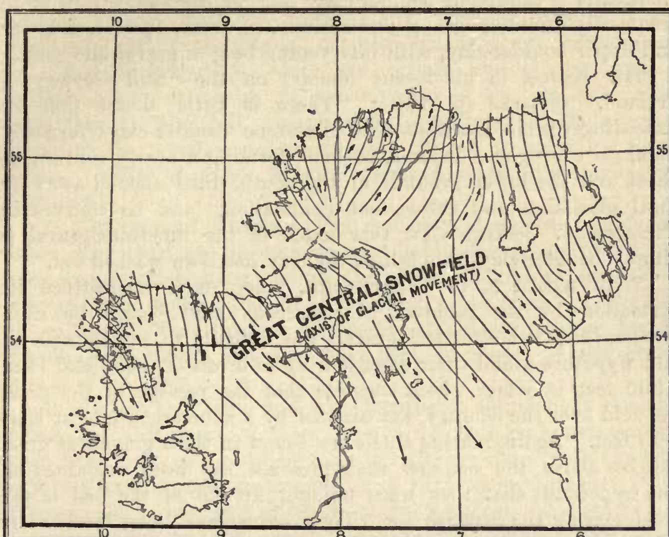


Fig. 75.—THE GLACIATION OF THE NORTH OF IRELAND (after Prof. Hull). (Reproduced by permission from Mr. Kilroe's paper (*Quart. Journ. Geol. Soc.* vol. xliv. p. 831).)

Both before and after this great extension of Scottish ice the north of Ireland had its own central snow-field, from which ice seems to have radiated outwards in most directions except to the N.E., where it was always blocked and diverted by Scotch ice (see Fig. 75). At the same time there were independent snow-fields in Donegal and Iar-Connaught, and others in the more southern parts of Ireland, namely, on the Wicklow Mountains, the Commeragh and Knockmealdown Mountains, those of West Cork and Kerry, and perhaps also the Slieve Baughty on the borders of Clare and Galway.

The results of this great development and invasion of ice are seen in the extensive Glacial deposits which are spread over every part of Ireland except the highlands above mentioned and some of lower elevation. The Drift is thickest and most continuous over the great central plain, and over the lower parts of Eastern and Southern Ireland. In these areas débris derived from the Carboniferous Limestones, not only in the form of boulders and stones, but also in that of calcareous mud or marl, make up the greater part of the mass. In the mountain valleys the material is frequently a calcareous boulder-clay, but on the plains it is more frequently limestone-gravel ; sometimes, however, there is a lower and upper boulder-clay, with intervening beds of gravel and sand.

Mr. Kilroe, in his recent Memoir on the "Soil Geology of Ireland," remarks (p. 140): "There is little doubt that an exceedingly wide distribution of limestone boulder-clays formerly obtained throughout Ireland, perhaps forming a nearly continuous sheet over the lower grounds of the south, until cleared away by local glaciation and subsequent denudation," and he concurs in Professor J. Geikie's view that much of the limestone-gravel is simply boulder-clay from which the clay has been washed out.

With regard to the latter point, where it is unstratified its formation by the removal of calcareous mud would be comprehensible, but stratified gravels are difficult to understand on this hypothesis, and their extension up to levels of 1200 and even 1300 feet is a fact which suggests that the passage of the great ice-field over the country was assisted by a submergence of at least 500 feet. Again, marine shells are found in these gravels at great heights above the sea, and their presence has been explained on the hypothesis that they were brought up out of the bed of the Irish Sea by the Scottish ice. Their occurrence along the borders of this sea might be accounted for in this way, but their presence at a height of 1300 feet so far south as Wexford seems unlikely, unless the land was lower than it is at present.

The upper boulder-clay generally differs from the lower in being a local drift, and the contrast is sometimes very marked. Thus near Bantry there are "limestone clays," the materials of which must have come from areas lying at a considerable distance to the north or N.W., and these clays are covered by a different clay, made up entirely of local detritus.

During the melting and retreat of the ice other superficial deposits were left on the great central plain in the shape of long, irregular ridges of gravel, which often extend more or less continuous for great distances. These are called *eskers* in Ireland, and are the same as the *kames* of Scotland.

B. *Geographical Changes on Land*

From the preceding descriptions it will be understood that after the acme of the Ice Age, when the ice began to retreat from the wide areas which it had covered and finally disappeared from all the lower parts of the country, the surface thus revealed would present a very different aspect from that of the pre-Glacial Pliocene surface. Apart from the peculiar and irregular features of the surface formed by the Glacial deposits, but as direct consequences of these irregularities, there are certain special geographical features which date from the passing away of the Ice Age; these are lakes in the hill districts, and the new channels which many of the streams and rivers were obliged to make for themselves. Each of these features deserves some description and illustration.

1. **Lakes and Tarns.**—The reader is doubtless aware that lakes may originate in various ways, some resulting from crust-movements which have altered the slopes of valleys, some from the solution of limestone or of rock-salt, some from the blocking of valleys by landslips, or the deltas of side-streams, or by the moraines of glaciers, and some have been attributed to the erosive power of ice itself.

It is a fact that lakes and tarns are always abundant in glaciated areas, and that some of them seem to be true rock-basins which may have been excavated by ice; but glaciers have probably been credited with a much greater power of excavation than they really possess. The mountain districts of the northern hemisphere had been exposed to the action of subaerial agencies for many thousands of years before the advent of the Ice Age, and the rocks of which they consist must have decomposed and disintegrated to a very great extent. It is a well-known fact that even the same kind of rock, such as granite, gneiss, or mica-schist, weathers very unequally in different parts of the same exposure, some parts disintegrating into loose sandy or clayey material, while others remain fairly hard.

It is obvious that if the loose material is removed by any detersive agent, hollows and basins will be produced which would naturally become ponds or lakes. Pumpelly has pointed out that in dry climates this can even be effected by the wind, and he has indicated certain basins in the crystalline rocks of Northern Asia as having probably been formed in this manner. It is therefore quite comprehensible that glaciers should have cleared out all such ready-prepared basins that lay in their paths, not only in the upper courses of their valleys, but wherever the ice pressed heavily on the underlying surface.

There are, however, a large number of lakes which are not rock-basins, but are held up by deposits of boulder-clay or morainic matter left during the retreat of the glaciers. The continuation of the original valley being blocked by these materials, a lake has been formed, and the excurrent stream either flows over the barrier or has found some other outlet. Of such lakes and tarns I propose to give a few instances.

A very good instance of a lake formed by the blocking of valleys by Glacial Drift is that of Loch Skene in Peeblesshire, described long ago by Dr. J. Young,[1] from whose account the following facts and illustration are borrowed. Loch Skene is 1680 feet above the sea, and is surrounded by mountain slopes except for openings on the south and the N.E. sides. In pre-Glacial times its site appears to have been the head of the Winterhope valley (see Fig. 76), which lies to the N.E., and is a wide valley filled with boulder-clay and moraines. This valley drains northward into the Megget Water, but Loch Skene is now drained southwards by Fail Burn into the Moffat Water, and the Fail Burn flows through a series of morainic mounds and ridges, which are mostly arranged in concentric curves, and extend for some distance down the valley, as indicated on Fig. 76.

The Lake District of Cumberland and Westmoreland also furnishes many cases of the formation of lakes in a similar manner, and of alterations in the courses of rivers from the same cause. Dr. J. E. Marr has shown that many of the tarns of Lake-land have dams of moraine at their lower ends;[2] such is Codale Tarn near Grasmere, where the continuation of the valley below the tarn is completely blocked by Drift, and the stream which now leaves the tarn issues from its eastern side and runs at right angles to the direction of the valley in which the tarn lies. Levers Water near Coniston exhibits similar features. Another interesting tarn is that of Burnmoor, between Eskdale and Wastdale, which is due to the blocking of the valley leading into Miterdale, the exit of the present stream being actually near the upper end of the lake, and draining by Whillan beck into Eskdale.

Some larger lakes seem also to have been formed in the same way, *e.g.* Windermere (and perhaps Coniston), Loweswater, Bassenthwaite, and Ullswater. Dr. Marr has pointed out[3] that the floors of Lakes Windermere, Coniston, and Wastwater are all in their

[1] *Quart. Journ. Geol. Soc.* vol. xx. p. 452 (1864).
[2] *Ibid.* vol. li. p. 35.
[3] *Proc. Geol. Assoc.* vol. xiv. p. 275.

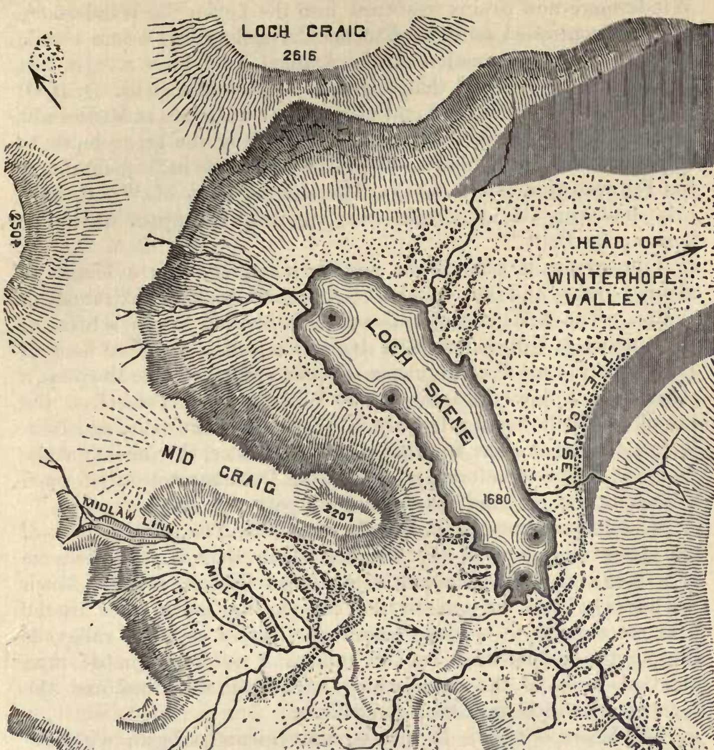


Fig. 76.—MAP OF THE COUNTRY ROUND LOCH SKENE (by Dr. J. Young). (Reproduced by permission of the Council of the Geological Society.)

deepest parts below the level of the sea, and that though Windermere now drains westward into the Leven the Windermere valley is continued southward to the Cartmel valley, where a wide and old-looking depression is now drained by a mere rivulet. It is consequently inferred that this depression is filled with Drift all the way from the southern end of the Lake to the sea at Morecambe Bay. The probability of this is increased by the great depth to which old valleys are known to be filled with Drift in the neighbouring Furness area (see p. 431). The deepest part of Windermere may, however, lie in a rock basin, and only the upper waters be kept up by Drift.

Loweswater is one of the smaller lakes, but has a length of about 2 miles and now discharges by Park Beck into Crummock Water. The N.W. end of Loweswater is banked up by a mass of Drift which is believed to fill a depression which with the floor of Loweswater was a continuation of the valley of the Marron, a stream which flows into the sea at Whitehaven. The col on the top of the Drift barrier is only 100 feet above the lake, and from it flow two brooks, one running into Loweswater, the other into the Marron. Here therefore a pile of Glacial Drift has not only formed a lake but has reversed the drainage of part of a valley.

2. Alterations of River Drainage.—The investigation of our river-valleys and of the changes which they have undergone is a fascinating and comparatively recent line of study. Much has already been written on the subject, but much work in the field yet remains to be done before the history of some valleys is thoroughly understood. In this volume I cannot do more than mention some of the cases which have been described and the conclusions which have been published.

The Severn Valley.—It will be convenient to begin with the Severn, which is now the longest river in England, but is believed to be the result of the union of two distinct rivers in consequence of the barriers created by the Glacial episode in Pleistocene time. The area concerned in this connection is that of North Shropshire and the plains of Cheshire, and its physical features are thus described by Mr. Harmer:[1] "The Cheshire plain, a Drift-covered Triassic region, lying for the most part below the 300-foot contour, with a gradual slope northward to sea-level along the basins of the Weaver and the Dee, is surrounded by high Palæozoic land; on the west by the Welsh mountains, on the south by the highlands of Shropshire, and on the east by the Pennine Hills." The only opening in the girdle is to the south-east, which was the route followed by the Irish Sea ice-field; it is probable, however, that

[1] *Quart. Journ. Geol. Soc.* vol. lxiii. p. 477 (1907).

before the advent of the ice all this watershed area was over 400 feet above sea-level.

As stated on p. 401, it is probable that the original course of the Upper Severn was northward, and that it was in reality the Upper Dee, having no connection with the Severn. Again, as Mr. Harmer remarks, "the gorge at Ironbridge has no natural connection with the Cheshire plain on the one hand or with the basin of the Lower Severn on the other, although it unites them artificially, as the Panama Canal may unite the Pacific Ocean with the Caribbean Sea, each cutting transversely across a narrow isthmus of high land."

Mr. Harmer believes that the advance of the Irish Sea ice blocked the outlets of the Dee and the Weaver, converting the whole Cheshire plain into a lake and ponding back all the rivers which flowed into it. He thinks that the ravine through which the Severn now passes near Ironbridge was formed when this ice had advanced as far as Wolverhampton, and had blocked all possible outflows eastward into the valley of the Trent, so that the only line of escape was between the ice-lobe and the high land on the west.

I am inclined, however, to doubt this view that the gorge at Ironbridge was formed at the epoch of maximum glaciation. I think it probable that the Arenig and North Wales ice, having far less distance to travel, would arrive first on the Cheshire plain, and would afterwards be deflected southwards by the Irish Sea ice, the two ice-lobes being then coterminous. If this were so it is more likely that the formation of the great Cheshire lake and of the overflow channel at Ironbridge took place after the greatest advance of the ice, and when the two lobes began to retreat. The Welsh ice having far less thickness of ice behind it, would retreat more rapidly than that filling the Irish Sea, which would probably remain almost stationary for a time; a space would consequently be left between them, and the conditions necessary for the formation of such a lake would be produced. Strong streams would issue from the border of the Welsh ice as it retired up the valleys, and the water would be ponded back from exit toward the north or west, just as Mr. Harmer supposes.

I see no difficulty in accounting for the southerly course of the river after leaving the ravine, for it must be remembered that the Lower Severn had been developing its valley system ever since Eocene time, and hence it was likely to have a tributary draining the area between Bridgenorth and Ironbridge. The overflow from the Cheshire Lake would therefore fall into a valley already prepared to receive it.

Durham.—The blocking of valleys by Drift deposits is well illustrated in Durham and Northumberland, where the surface changes thus produced have been studied by Dr. D. Woolacott, from whose paper[1] the following account is taken. He remarks that in pre-Glacial times the land must have stood much higher than now, for the rock floors of some of the Drift-filled valleys are 140 feet below sea-level. The valleys in which these deposits lie are those of the Tertiary rivers, and the courses of the modern rivers differ much from the older waterways.

Though many of the rivers still flow in the direction of their original valleys, they have often left these and have cut new channels, sometimes through solid rock, sometimes through boulder-clay. In many cases they keep to the edge of the old valley, cutting a new channel between the rock-slope of the valley and the infilling of Drift. In explanation of this peculiarity, Dr. Woolacott suggests that the surface of the Drift in the valleys was a convex curve, following the surface of the ice which produced it, so that the post-Glacial stream found a natural channel where this surface met the valley-slope.

In pre-Glacial times the escarpment of the Permian Magnesian Limestone was a bold feature, running through the county of Durham from south to north and ending at South Shields, near Tynemouth. West of this escarpment (see Fig. 77) was a broad strike-valley, formed and occupied by the river Wear, which flowed northward below the site of Durham city and through the valley of the Wash to join the Tyne near Newcastle. The whole of this valley was, however, filled with Drift during the Glacial episode, the depth of such deposits being still in many places over 150 feet, and in one place near Durham a boring proved 233 feet. After the melting of the ice the river reoccupied the valley, cutting a new channel over the irregular surface of the boulder-clay; but the Drift-mounds must have been so high around Pelton and Urpeth that the river was compelled to turn eastwards and make a new course for itself over the partially buried escarpment of the Permian Limestone, and through this limestone to Sunderland.

Vale of Pickering.—The history of this valley up to Miocene time has been told in Chapter XIV., and the barrier of boulder-clay at its eastern end has been mentioned on p. 400. In Pliocene time the valley must have been occupied by a river which flowed eastward, and was fed by numerous tributaries coming from the Cleveland, the Hambledon, and the Howardian Hills. The actual valley of this river, which we may call the Rye, cannot now be

[1] *Quart. Journ. Geol. Soc.* vol. lxi. p. 64 (1905).

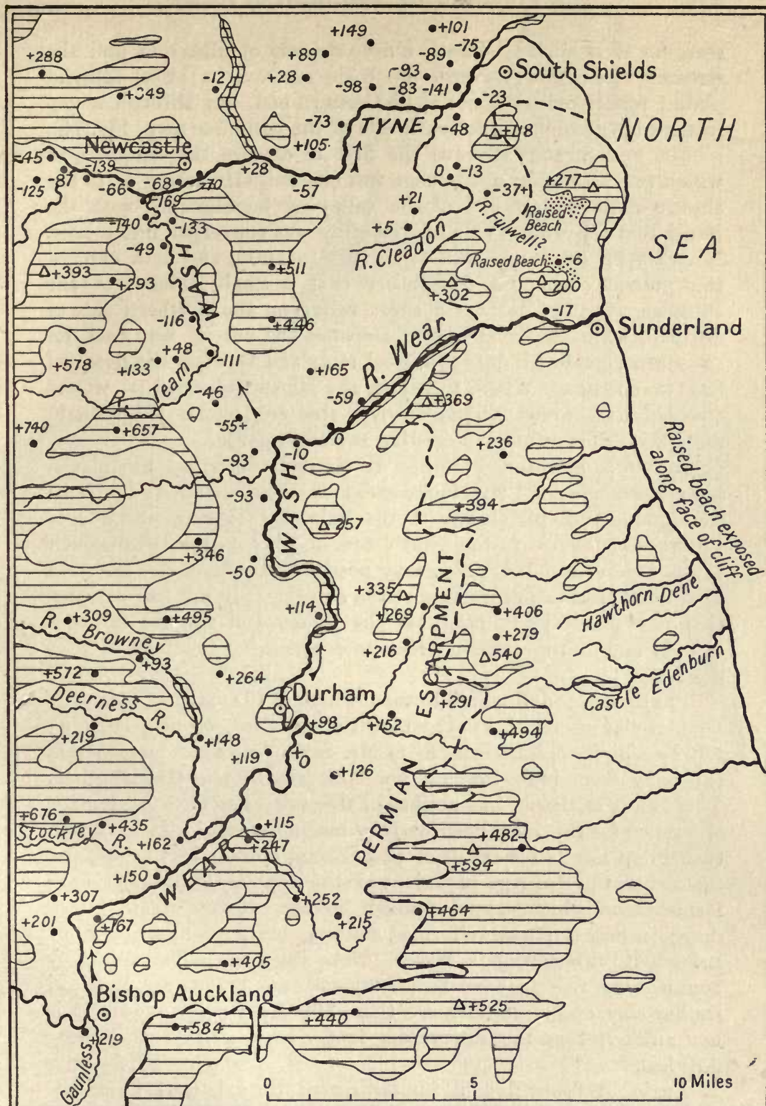


Fig. 77.—MAP OF THE PRE-GLACIAL VALLEYS IN DURHAM (by Dr. D. Woolacott). (Reproduced by permission of the Author and the Council of the Geological Society.)

seen, for it is buried beneath a deep deposit of alluvium, and the streams which now traverse the basin run over a broad alluvial plain ; finally escaping, not at the eastern end, but through a gap in the high ground on the south side of the basin (see map, Fig. 78).

Mr. Fox Strangways was the first to explain the manner[1] in which this alteration of drainage was effected, attributing it to the closure of the eastern end of the valley by boulder-clay, with the result that the whole Vale of Pickering was converted into a lake. Mr. Cowper Reed took the same view in 1900, and both explain the present outlet on the theory that a small affluent of the Pliocene river had formed a short valley on the northern side of the gap, while the head of the Derwent had cut its way back on the southern side till only a low col remained between the heads of the two streams. When, therefore, the lake was formed its waters rose till they found an outlet over this col, which they would rapidly cut down into the existing ravine or gorge.

In 1902, however, Professor P. Kendall described the glacial phenomena of the Cleveland district in great detail, and formed the opinion that the closure of the Vale of Pickering was due to the mass of the ice in the North Sea, and not to the Drift-barrier which it left behind.[2] This may possibly have been the case, but in spite of his elaborate study of the subject I do not feel satisfied that it is necessary to postulate the presence of massive ice-lobes at each end of the vale in order to account for the formation of the lake.

Professor Kendall points to the lowness of the existing barrier of boulder-clay south of Filey, where the cliffs are in one place only 130 feet high, and he demurs to Mr. Strangway's assumption that this may have been lowered by 100 feet in post-Glacial time. This is fair criticism, but neither of the writers seem to have made allowance for the land destroyed by marine erosion. It is certain that Filey Bay is the result of post-Glacial erosion by the sea, and that when the Ice Age passed away the Glacial Drift must have formed land which extended much farther eastward than it now does; in fact it probably formed a strong barrier connecting Filey Brigg with Flamborough Head. Near Filey the cliffs capped by boulder-clay rise to over 200 feet, and on Flamborough Head similar clay occurs up to more than 300 feet; consequently it is not unlikely that the intervening land rose to a level of at least 250 feet.

Again, Professor Kendall himself records the existence of boulder-clay at an altitude of 279 feet in the Coxwold-Gilling valley at

[1] "Valleys of N.E. Yorkshire," *Leicester Lit. and Phil. Soc.* (1894).

[2] *Quart. Journ. Geol. Soc.* vol. lviii. p. 556.

Fig. 78.—CONTOURED MAP OF THE VALE OF PICKERING (by F. W. Harmer). (Reproduced by permission of the Author and the Council of the Geological Society.)

the western end of the vale, and thus both ends of the great depression were probably blocked to a sufficient height by Drift. Further, it seems to me more likely that the formation of such a large sheet of water would take place when the climate became less rigorous and the ice began to melt, rather than at the time of maximum glaciation, when the whole region was frost-bound.

Lincolnshire.—The features presented by the valleys of Durham are repeated in Lincolnshire, and some of them were described by me in the years 1883-1885.[1] Moreover, some occur in positions where blocking by ice is very improbable, and where the actual Drift barriers still remain across the valley-ways. Thus near Hatcliffe,

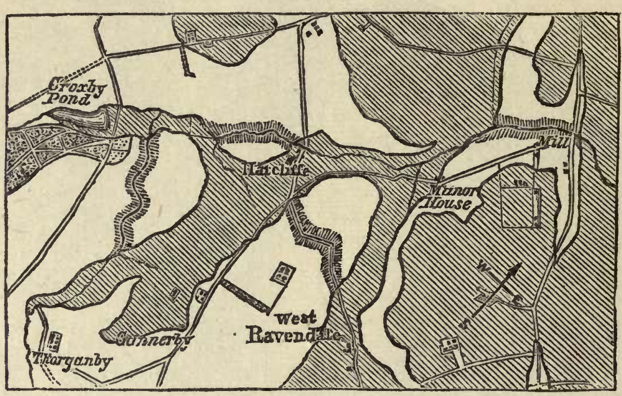


Fig. 79.—MAP OF THE COUNTRY ROUND HATCLIFFE IN LINCOLNSHIRE. The Glacial Drift is indicated by diagonal lines. (From the *Quart. Journ. Geol. Soc.*)

about 6 miles east of Caistor, there are no less than four new cuts made by streams through Chalk in different parts of one little inland valley system. Fig. 79 is a sketch-map of this district, the ancient valleys near Hatcliffe being indicated by the Drift-shading, and the recent ravines by the lines across the intervening Chalk ridges. The principal mass of Drift occupies the depression between Thorganby and Hatcliffe, mounds of gravel, sand, loam, and boulder-clay being here so mingled that it was impossible to map them separately. The stream coming from above Thorganby has been diverted by this mass of Drift and has cut a narrow gorge about 100 feet deep through the Chalk ridge on the western side, emerging into an old tributary valley just below a great mound of boulder-clay, which has blocked its drainage and caused the formation of a small lake known as Croxby Pond.

[1] *Quart. Journ. Geol. Soc.* vols. xxxix., xl., and xli.

Still unimpeded by the mounds of Drift filling the old valleys, the modern brook has cut a second ravine through the Chalk near Hatcliffe, and a third still lower down ending at Hatcliffe Mill. The fourth ravine is that between West Ravendale and Hatcliffe, but this is now dry, the Ravendale beck now running northward along the border of the boulder-clay tract. It may be inferred that this was originally higher than the Chalk ridge, and that at first the brook made and ran through the ravine, but was subsequently captured by a rivulet working back up the pre-existing valleys.

Cambridge and Hertford.—Examples of Drift-filled valleys also occur in these counties, and an interesting case has recently been described by Mr. W. Hill.[1] This buried valley begins in Langley Bottom, a dry valley about 4 miles S. of Hitchin, and has been traced northward by Hitchin and Ickleford to Holwellbury, a distance of about 8 miles. Though Chalk comes to the surface in places at Hitchin a boring there was carried through Drift to a depth of 340 feet, when it entered the Gault. Moreover, at Hitchin the valley-floor is 68 feet below sea-level, and it seems probable that it opened northward into some ancient valley below that of the Ouse, when the whole country stood at a much higher level. The deposits with which it is filled consist chiefly of gravel, which is generally stratified, but patches of the boulder-clay occur both in and over the gravels.

C. *Changes of Level*

At the close of Pliocene time, as described in Chapter XV., England was united broadly to France across the English Channel, and the Straits of Dover did not exist. It has also been thought that Britain was united to Ireland, and such a connection may have continued for a time; but the space between England and Ireland was certainly occupied by the sea when the ice-sheets descended into it, and the depth of this space in Pliocene time must have been much greater than the present depth of the Irish Sea, for it carried off rivers which ran into it at depths of 300 to 450 feet below sea-level on the Lancashire side.

It is only in recent years that some geologists seemed to have realised what these buried and Drift-filled valleys really mean. They do not prove that the whole country stood at a correspondingly high level *just before* the Glacial episode, but they do prove that the North Sea and the seas surrounding Ireland must be underlain by, and partially filled with, a great thickness of Glacial Drift.

The pre-Glacial valley of the Mersey is known to be at least

[1] *Quart. Journ. Geol. Soc.* vol. lxiv. p. 8 (1908).

160 feet below sea-level, and a valley in Furness descends to 450 feet. These and other valleys are doubtless continued westward beneath the shallow eastern part of the Irish Sea, which is nowhere more than about 200 feet deep. The deeper part of this sea lies entirely to the west of Anglesey and the Isle of Man, where depths of from 50 to 70 fathoms occur, and in one deep hole 80 fathoms. This, however, is only 480 feet, and if the Furness valley is prolonged in a S.W. direction for 100 miles, it is not likely to fall less than 200 feet in that distance, so that we may infer the actual rock-floor of the Channel between Anglesey and Dublin to be not less than 650 feet below the surface of the sea, and some 300 feet below its present floor; that 300 feet representing the thickness of Glacial Drift in St. George's Channel.

Turning to the other side of Britain, we may again ask what thickness of Glacial Drift is likely to underlie the great plain of the North Sea floor, and whether the Dogger Bank is more than a heap of boulder-clay left in the middle of it. The latter question cannot be answered till a boring has been made on the Dogger Bank, an operation which I am informed is quite feasible, and would be merely a matter of expense and arrangement, for of course it could only be carried out in fine summer weather.

Between England and Denmark the North Sea is everywhere less than 50 fathoms deep, the average depth round the Dogger Bank being about 35 (= 210 feet). Considering the mass of ice which filled this sea in the Glacial episode, it may well have left an average thickness of 300 feet of Drift deposit behind it, so the pre-Glacial floor of the North Sea may now be 500 feet below the present sea-level.

The deepest buried valleys yet proved along the coast of Durham and Northumberland are 170 and 200 feet below sea-level, and would therefore easily drain into an area which was 300 feet deeper; but farther north, near Bo'ness on the Firth of Forth, borings have revealed a buried valley which is more than 500 feet below sea-level,[1] and is probably the valley of the Pliocene river Forth. Now the slope of the North Sea floor east of the Firth of Forth does not reach a depth of 50 fathoms for a distance of 80 miles. This depth is only 300 feet, and the old river would certainly fall another 100 feet in the distance, so that again the bottom of the old estuary under the North Sea is probably 300 feet below the present irregular floor.

As above remarked, it is a mistake to suppose that the existence of valleys descending far below the sea-level is proof of the high elevation of the land at the beginning of the Glacial epoch. It

[1] See *Sum. Prog. Geol. Survey* for 1904, pp. 108, 109.

only proves that at some pre-Glacial date the land stood at such a high level. We have seen that the process of valley-making went on without interruption in the north of England from Eocene and Oligocene times, and that the greatest elevation attained by the land was either in Oligocene or Miocene time. During the Pliocene epoch the whole of North Britain must have been gradually sinking, with the gradual formation and extension of the North Sea; but the infilling of the old valleys with Pleistocene deposits proves nothing—they might have then been at the same relative level as they are now, or they might have sunk to their present position during the Glacial episode.

There is evidence, however, which indicates that when the North Sea ice reached the east coast of England the sea-level was nearly the same as it is now. Thus the Pliocene series of Norfolk closes with the marine *Leda myalis* Bed, above which is the Arctic plant bed, both being very little above the present sea-level, and no indication of any great change of level having taken place between the deposition of the two beds; only a change from a cold to an almost Arctic climate.

Again, a pre-Glacial line of cliffs extends all along the eastern side of the Lincolnshire and Yorkshire Wolds, beginning at Welton in Lincolnshire and running N.W. by Alford, Louth, Riby, and Ulceby to the Humber near Barton. In the boulder-clays which are banked up against this cliff are lenticular beds of gravel, sand and loam containing marine shells, as well as stones bored by *Pholades*. In Yorkshire it starts again at Hessle, near Hull, and can be followed northward by Cottingham and Beverley to Driffield, where it curves to the N.E. and is intersected by the present line of coast at Sewerby near Bridlington.

The level of old beach line, both at Sewerby and Hessle, is practically the same as that of the modern beach, and the Humber was an estuary as it is now, but its mouth opened directly through the line of cliffs into the sea. Thus the whole of Holderness and the lowland of East Lincolnshire is a gift of the Great Ice Age, for these areas consist entirely of Glacial deposits down to depths of 80 and 100 feet below sea-level, and the marshes have been formed on the hummocky surface of the boulder-clay.

At the same time, I cannot find any geological evidence for supposing that the Glacial epoch was a time of high elevation: on the contrary, the facts suggest a greater probability of its having been a time of subsidence, though I admit that the presence of sea-shells in Drift at high levels does not prove a submergence of the heights at which they are now found. Their presence, however, does prove that the Irish Sea was practically as extensive as it now is, if not of greater extent, for any considerable elevation would have converted it into dry land.

In Scotland shells have not been found much above 500 feet, and at the time of maximum glaciation the Scottish ice-sheet must have been much more than 500 feet thick on the lowlands, so that if the country were then 500 feet lower than now the base of the ice would still be passing over the submerged surface, displacing an equal depth of water, and marine deposits could not be formed under it till it loosed its grip.

The subsidence may have been greatest in the north, and have lessened southwards to less than 100 feet in South Wales, but any such subsidence would greatly help the ice-fields to invade the English lowlands, as they clearly did both from the N.E. and the N.W.; and it would also account for the extension of the ice over the whole central plain of Ireland, the greater part of which is not more than 300 feet above the sea.

There is actual evidence of a pre-Glacial or inter-Glacial subsidence in South Wales, the south of Ireland, Devon, and Cornwall, where raised beaches occur at heights of from 15 to 25 feet and in places up to 40 or 50 feet in South Wales. Some of these are overlain by boulder-clay, many by the local bouldery material known as "head," and there is good reason to think that they are all of the same age, and that they belong to an early part of the Glacial epoch.

Dr. Strahan,[1] writing of the beach which is overlain by pre-Glacial Drift in Gower, says: "It is certain that the beach preceded the first manifestation of Glacial phenomena in those spots where it occurs." It is probable, therefore, that the Gower beaches belong to an early date in the Ice Age, because they occur so far south that conditions favouring the production of boulder-clay in that area are only likely to have prevailed at the time of greatest ice-extension. Consequently they testify to a subsidence either just before or during the episode of maximum glaciation.

We now come to the question of the Pleistocene land connections of the British Isles. There can be little doubt that England was united to France across the Straits of Dover at the beginning of the period; and though subsidence certainly took place during the Glacial epoch, I see no reason for supposing that complete severance took place until quite a late date in Pleistocene time.

Raised beaches and marine gravels occur at intervals along the south coast of England from Torbay to Brighton, and the facts connected with them are both curious and instructive, for though

[1] "Geology of the Country around Swansea," *Mem. Geol. Survey* (1907), p. 118.

they are probably all of the same age they are by no means at the same level. We must remember, however, that a modern beach situate near a promontory may be deeply covered at high water, while one at the head of a bay may only be reached by the waves at high spring-tide ; so that the latter may be 20 feet above the level of the former.

The base of the raised beach at Hopes Nose near Torquay is about 25 feet above high water, and as its upper part appears to be blown sand, this beach was probably formed at the head of a small bay, and consequently at the highest beach-level of the time. No undoubted raised beach occurs round the great bight of the coast between Torbay and Portland Bill, where a beach containing marine shells is found at 24 feet above the present beach, but the level rises inland to 53 above that level, and ends at the base of a raised cliff.[1]

In Hampshire and Sussex marine gravels extend inland and terminate against the foot of an ancient line of cliffs which in some places is partly hidden by them, in other places well exposed. Thus on the south side of Portsdown Hill a beach gravel occurs up to 100 feet above the sea, and near Arundel, within a few yards of the inland cliff, sand with marine shells is found at a height of 130 feet. Thence the old beach can be traced eastward to Brighton, its level declining till where it is intersected by the present coast-line it is only 18 feet above mean sea-level. The beach deposit is often overlain by the material known as "Coombe Rock," which is probably contemporaneous with the "head" of Devon and Cornwall, and with the coastal Glacial Drift of South Wales.

No raised beach of the same age has been found to the east of Brighton, even in places favourable for the preservation of the ancient cliff-line if it had been continued inland of the present coast. Again, on the French side, raised beaches occur at many places along the coasts of Brittany, the Channel Islands, and the Cotentin, and there is a deposit containing marine shells near Abbeville at about 24 feet above mean sea-level ; but no traces of such raised beaches have been found on the French side of the Straits north of the Somme, till we come to Sangatte near Calais, where there is a beach with overlying deposits like those of Brighton.

These facts are very significant, and in spite of Professor Prestwich's opinion to the contrary, I adhere to the view I have previously maintained that they indicate the existence of an isthmus of land, still remaining across the Straits of Dover, at

[1] See Prestwich, *Quart. Journ. Geol. Soc.* vol. xxxi. p. 33.

the time when the old beaches were formed. If this was so, then the northern shore of the Channel passed eastward from Brighton, backed by a continuation of the South Downs, to some point on the French coast north of Abbeville, the Channel being a gulf which terminated at the estuary of the Somme (see map, Fig. 80, by the name Vallery).

The beach at Sangatte I take to be part of the southern shore of the North Sea, the North Downs being partly or wholy breached by an inlet leading in the direction of Romney Marsh; so that

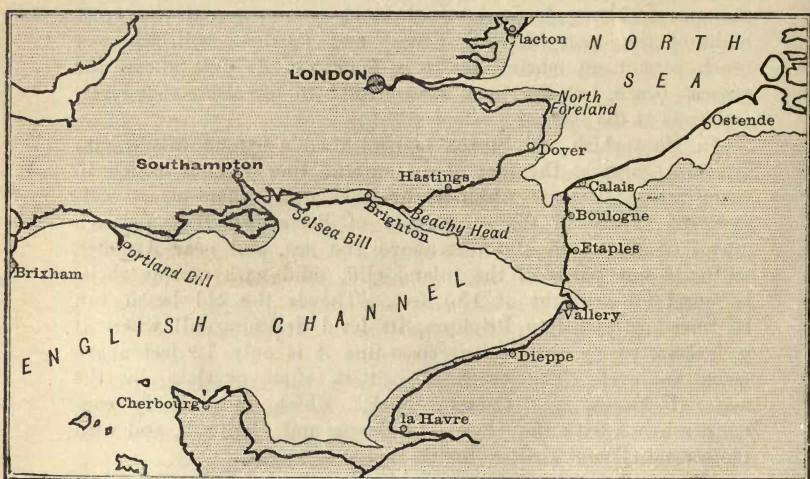


Fig. 80.—GEOGRAPHY OF THE CHANNEL AREA AT THE TIME OF THE RAISED BEACHES. The thick lines indicate modern coasts, the thinner lines those of the ancient coasts.

the gap which now forms the Straits of Dover had been commenced, but did not extend far to the southward.

The greater height to which the old beach-line reaches in Hampshire and West Sussex, as compared with its level at Brighton and in Devonshire, suggests some differential movement, either during the succeeding elevation, or during the still more recent subsidence. If its low level near Brighton is due to a greater subsidence of the south-east of England, the severance of England from France would be completely accounted for.

After the subsidence indicated by the raised beaches, but probably before Glacial conditions had passed away from Northern England, a movement of upheaval seems to have taken place.

This may be inferred from the beds of peat and submerged forests which are found all round the English coasts at various levels below the sea-level, from 20 feet below high-water mark to as much as 67 feet near Falmouth (according to Pengelly). In South Wales a bed of peat in Swansea Bay is 44 feet below the level of the lowest alluvial flat which is not flooded at high tide, and near Cardiff peat occurs at 55 feet below a similar level.

From these facts we may infer that when these peat and forest beds were formed the land stood at least 60 feet higher than it does now, and possibly more, for forests do not grow on alluvial levels. It is important also to note that when the land stood at this level and the valleys were clothed with forests, the raised beaches of Devon and South Wales would be from 80 to 100 feet above sea-level.

This elevation seems to have been a general one, extending both to Ireland and Scotland. In the latter country there is a succession of raised beaches which occur at intervals along both the eastern and western coasts, but are best preserved in the west. The most constant and conspicuous terraces are those at levels of about 100, 50, and 25 feet above mean sea-level. The first is, of course, the oldest, but is probably later than the raised beach of Southern Britain, for it cuts into the coastal boulder-clays. The second coincides with the head of the upper carse-lands (or alluvial flats) of the Firths of Forth and Clyde, and its nearly level surface winds as a grassy terrace along the sides of many of the lochs and inlets of the west coast.

The third terrace, at 20 to 25 feet above sea-level, is of course the newest and also the clearest of all. Sir A. Geikie describes it as "running down the more sheltered indentations of the coast-line as a flat selvage of rock, or of littoral deposits, varying in breadth from 6 or 7 miles to not more than a few feet. Its deposits are horizontal layers of sand, gravel, or clay, often full of littoral shells."[1] The inland cliff at the back of this terrace is often hollowed out into caves like those of the present sea-margin. On the east coast it forms a broad terrace on both sides of the Firths of Forth and Tay, and indeed it is traceable in sheltered bays all round the eastern and northern coasts. On the west it is conspicuous along the Firth of Clyde and southwards along the coasts of Ayr and Wigton. The same beach-line is also believed to occur in the N.E. of Ireland.

The carse-lands above mentioned are features peculiar to Scotland, being raised alluvial flats which have no counterpart in England. Thus the lower carse of the Forth is a flat tract

[1] *The Scenery of Scotland*, 3rd Edition (1901), p. 412.

of ground from 25 to 30 feet above sea-level, and consisting of brown clay about 20 feet thick, which contains marine shells. At the base of this clay is generally a bed of peat, which often crops on the shore of the estuary, and evidently had a seaward prolongation. Below it is soft pale-grey clay, probably also of marine origin.

Returning now to England, we find similar marine deposits and *Scrobicularia* clays, but they are generally below sea-level. These are associated with the submerged forests and peat beds already mentioned, the position of which proves that the last movement of the English area was one of submergence. It was doubtless by the aid of this subsidence that the sea was enabled to cut through the isthmus which had hitherto connected England with France, and thus to form the Straits of Dover.

Great Britain was thus finally reduced to the condition of an island, and has since suffered considerable loss of land by marine erosion along certain portions of her coast-line. This loss, however, has been partially compensated by gain of land in other localities, and these changes have really been in progress from Neolithic time up to the present day. The subsidence which severed us from the Continent carried the sea over certain low-lying areas, but when the movement slackened or ceased, these areas began to be silted up ; in this manner were formed the extensive fens and marshes which occur at so many places along our southern and eastern coastlands.

Thus the Building of England has been going on up to quite a recent date, and has been assisted by the efforts of man in banking out the sea from these fens and marshes. By this means large areas of bog and fen have been converted into good agricultural land, such as the Somerset marshes, Romney Marsh, Pevensey Level, the great Fenland of Cambridge and Lincoln, and the Marshland of East Lincolnshire.

There remains only the question of the severance of Ireland from England, which is bound up with the question of the manner in which the Pleistocene fauna reached Ireland. There are indeed two groups of facts to be explained : (1) the introduction of the early Pleistocene fauna into Ireland ; (2) the subsequent immigration of the fauna found in the peat-bogs and that now inhabiting the country.

In Irish cave-deposits bones of the following animals have been found—the Mammoth (*Elephas primigenius*), the Irish Elk (*Cervus giganteus*), *Hyæna spelæa*, two or three species of Bears, two species of Lemming, with the wolf, the fox, and the wild boar. This fauna is similar to that found in the caves of South Wales, and implies a cold climate. Its introduction into Ireland has greatly exercised the minds of geologists and naturalists, but many have taken it for granted that when this fauna reached Wales there was sea between the two countries. Hence some have supposed that there was an elevation of greater or less extent in the middle of Pleistocene time, or else that the animals passed over the surface of the ice which filled St. George's Channel.

I cannot see, however, that any real difficulty exists. It will be remembered that good reason was found for thinking that the western part of the British region did not participate in the subsidence by which the North Sea was formed, but remained at a comparatively high level; so that during the later part of Pliocene time Ireland was still united to England and Scotland (see map, Fig. 72). There is no reason why these geographical conditions should not have continued into the Pleistocene period, while the climate gradually became colder and glaciers began to be formed on the mountains of Scotland and Wales.

Even if the region was slowly subsiding it would be some time before the great river valley between Wales and Ireland was converted into an estuary; and meantime early Pleistocene animals could cross over into Ireland as easily as they did from the Continent into England. On this point, therefore, I am in agreement with Dr. Scharff, though I cannot assent to all the other details of his map of the geography of Europe at the beginning of the Glacial epoch on p. 156 of his *History of the European Fauna.*

It is less easy to account for the introduction of the Neolithic and the modern fauna into Ireland, because it is agreed on all hands that the space between England and Ireland was occupied by the sea when the great ice-sheet extended itself down this depression, and spread outwards over the lowlands on each side of it. It thus becomes a question whether the sea remained after the ice retreated, or whether any subsequent uplift was sufficient to form once more a connection between the two countries.

The Neolithic fauna includes three large animals, *Cervus giganteus* (the Irish Elk), *C. elaphus* (the Red Deer), and *Rangifer tarandus* (the Reindeer); the first of these may have survived from early Pleistocene times, but the other two appear to be post-Glacial immigrants. The Red Deer still lives in Ireland, and there are many other members of the existing fauna which cannot be survivals from early Pleistocene time.

We have seen that after the Glacial submergence there was a partial recovery and re-elevation of the land. It has also been pointed out that though we have no proof that any part of our seaboard rose to more than 60 feet above the present sea-level, yet there is no reason why the elevation attained may not have been greater. The evidence that the land stood at least 60 feet higher is that of the buried peat-beds below the mouths of estuaries, and, for aught we know, these peat-beds (or land-surfaces) may be continued for a long distance outward under the floor of the adjoining sea, passing with a gentle slope to greater depths. Thus it is quite possible that they reach to 100 or 150 feet below sea-level.

It should also be remembered that farther east in Hampshire and Sussex the marine deposits of early Pleistocene age have been raised to 130 feet above the sea, and that in the same area there is evidence of subsequent subsidence to at least 30 feet (Portsmouth Harbour). Consequently the original uplift there amounted to at least 160 feet, and the contemporaneous elevation of Wales may have been just as much, the present difference in the height of the raised beaches being due to greater subsequent subsidence.

I would also suggest that the present contours of the floor of the Irish Sea may not even represent the surface-features of the Glacial deposits left by the retreating ice, but may have resulted from the subsequent erosion and modelling of their original surface during the subsequent elevation and the still more recent subsidence. The deep water channel in particular, which runs from south to north, may have been carved out of a more even plain of Glacial Drift during a pause in the last subsidence.

In other words, after the ice had retreated and elevation took place, the accumulation of Drift on the sea-floor may have been so great that a much less uplift was then needed to unite the two countries than would be necessary at the present day. Hence an uplift of 150 feet (25 fathoms) might have been ample to form a continuous land-surface between Wales and Ireland, as well as between the N. of Ireland and Scotland. I think, therefore, that it was at this time and in this way that Neolithic man and the Neolithic fauna made their way into Ireland.

Then came subsidence and the final severance of Ireland from Great Britain. Moreover, there is evidence that this separation occurred before England was severed from France. This is indicated by the peculiar distribution of species, especially of the mammals and reptiles, at the present time. The facts were first pointed out by Professor E. Forbes, and have been more fully investigated by Mr. A. R. Wallace,[1] who gives the following figures :—

Germany	has	90	species of Mammalia.	
Britain	„	40	„	„
Ireland	„	22	„	„
Belgium	has	22	species of Reptilia and Amphibia.	
Britain	„	13	„	„ „
Ireland	„	4	„	„ „

We must suppose, therefore, that the land did not remain very long at the elevation shown in Fig. 72, and that the isthmus between England and Ireland was submerged before more than four out of the twenty-two continental species of reptiles had crossed in sufficient numbers to effect a permanent settlement in Ireland.

I have now brought the history of the gradual process of building up and carving out of the British Isles down to the final phase of separation from one another and from the continent of Europe. The history is a long one, because it takes us back to the very earliest period of geographic development, when water first began to accumulate on certain parts of the earth's surface.

The earlier phases of the geographical evolution of the British region are more or less obscure and uncertain, because of the comparatively small knowledge which we possess of those periods; but the nearer we come to Pleistocene time the more evidence is available for such geographical restorations, and consequently if the facts have been properly interpreted, the more accurate should each succeeding restoration be. The reader will have perceived, however, that many questions still remain for final settlement in the light of further information when that can be obtained.

[1] *Island Life*, 2nd Edition (1892), p. 338 *et seq.*

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THE END.

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